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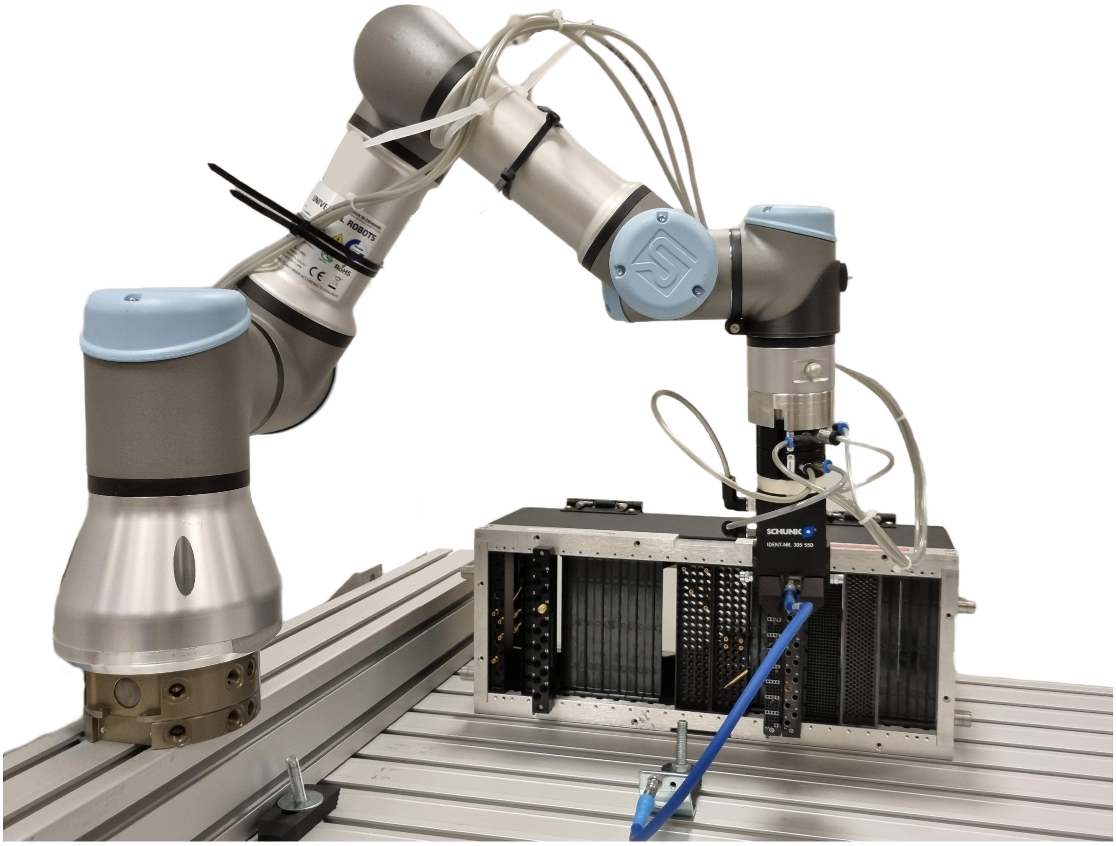

Smart Factory: Automated Calibration Operations

A Study of Implementing Collaborative Robots to Increase Test-Equipment Availability and Calibration Quality

Master's thesis in Production Engineering

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Master's thesis 2024

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Cover: Workstation consisting of an UR3 robot holding a coaxial cable and a connection interface with multiple socket variants.

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Abstract

Calibration of test systems is a crucial part of radar production to ensure high-quality products. The calibration process comprises many repetitive steps performed manually by operators. The process is time-consuming, which impedes the value-adding product testing in the test systems. This thesis investigates the potential for automating manual calibration processes. Furthermore, it aims to analyse the impact this would have on the availability of the test systems and the calibration quality. This was done through a process split into three distinct steps. First, a literature study focusing on collaborative robot technologies. A current state analysis was then performed to examine the current calibration process. Lastly, empirical testing was conducted by programming a collaborative robot to perform manual calibration tasks, mainly focusing on connecting and disconnecting connectors. The findings indicate that the majority of the tasks in the calibration can be performed by a collaborative robot equipped with a laser sensor and custom grippers for manipulating the cables. Some types of connectors are more challenging to handle using automation, suggesting that the process might still require an operator for certain steps, if not redesigned. The anticipated change in availability for a fully automated solution is minimal, as manual calibration will not be conducted frequently enough. An automated solution can improve calibration quality by performing tasks with better precision than operators. Nevertheless, the use of a cobot will result in greater equipment wear. The automation within this type of production environment has proven challenging, but the potential benefits of successful implementation should not be overlooked.

Keywords: Automation, Calibration, Cobot, Collaborative Applications, Connectors, Industry 4.0, Smart Factory.

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Finally we would like to thank our examiner Björn Johansson for providing helpful feedback and for taking on the task of examining this project.

William Karlsson & Eskil Thulin, Gothenburg, June 2024

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

ATE	Automated Test Equipment
CSA	Current State Analysis
ITA	Interchangeable Test Adaptor
KPI	Key Performance Indicator
LoA	Levels of Automation
LoA_c	Levels of Cognitive Automation
LoA_p	Levels of Physical Automation
LoC	Levels of Collaboration
OEE	Overall Equipment Efficiency
RF	Radio Frequency
SSM	Speed and Separation Monitoring
TCP	Tool Centre Point
TRM	Transmitter and Reciever Module

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1

Introduction

This chapter presents the background of the problem along with the aim and scope of the study to provide context as to why it was performed. Furthermore, limitations, environmental aspects and ethics will be discussed. Finally, a thesis outline is included to give a clear understanding of how the report is structured.

1.1 Background

In today's dynamic and competitive market environment, many companies are pursuing efficiency and productivity as key goals. They seek a competitive edge and increased growth. During the current era of Industry 4.0 many businesses move towards using more digital tools and automation for developing and refining their business practices. Cyberphysical systems, industrial automation, data collection and the Internet of Things are all concepts that are included in Industry 4.0 and companies use these concepts with an aim of streamlining operations and also further improving their efficiency [1].

Saab is a global company with 17000 employees in over 30 countries and consists of four main business areas [2]. The first one, *Saab Aeronautics*, develops and produces world-class aircraft systems, both for military and civil applications. *Saab Dynamics* works with sensors, deception systems, training and simulation systems, missiles, and support weapons amongst other technical solutions for the defence and commercial markets. *Saab Surveillance* covers a wide array of areas, including developing solutions for safety, security, surveillance, and threat detection. This department is where this master's thesis is based. Finally *Saab Kockums*, specializes in naval systems, submarines and surface vessels.

Saab Surveillance produces everything from small components to complete radar systems. One part of Saab is their production of transmitter-receiver modules (TRM), a key component in their radar systems. Depending on the radar system, the number of TRM required can vary, and are often many. To secure the quality of the TRM, advanced test systems are used in various parts of the production. These test systems are calibrated regularly to ensure the correct parameters and accuracy of the test systems. Calibrating the test systems is time-consuming and involves multiple manual steps. The test systems have a low overall availability and are considered a bottleneck in the production system. Saab is looking to move towards smarter manufacturing and benefit from all of the improvements that modern technologies can bring. A new and smart production line for testing products is therefore under development.

1.2 Aim

This project aimed to investigate how the calibration process could be improved with regards to availability and quality, at Saab in Kallebäck, Gothenburg. The project also aimed to investigate the possibilities of an automated calibration process by analysing different automation technologies. Furthermore, recommendations were given for an automated calibration process along with the expected impact on the performance that could be expected from implementation. The expected outcome of this project was improved availability and quality of the test equipment in the new production line. The implementation of advanced technology was intended to serve as a stepping stone for Saab in their journey towards smarter manufacturing.

1.3 Limitations

This master's thesis was conducted for approximately 20 weeks in the spring of 2024 at Chalmers University of Technology. The project was limited to only investigating test systems modules connected to a specific product at Saab. There are more types of calibrations that will not be considered for this project due to the process being dissimilar to what is expected to be present in the Smart Factory. If any physical solutions were developed, they would be more of a proof of concept rather than fully developed solutions that master the entire calibration process. Another limitation was that only available equipment would be used for the physical concepts. The production line where this solution was to be implemented was under development, which limited the possibility of validating the solutions in the real environment. The project was focused primarily on solving physical automation problems, hence not including software solutions for test equipment. There are already automated calibration programmes, but the bottleneck is in the manual process which is why this decision was made. Consequently, technologies such as robotic control systems or data management in the system were not researched. Due to the limitation of resources, technologies such as vision and sensors were not tested physically but rather evaluated using technical data and relevant research within the subject.

1.4 Scope of Study

To concertise the purpose of the thesis the following research questions were created.

- *How can automation technologies be implemented to improve the availability of the test-equipment and calibration quality?*
- *What automation technologies are most suitable for calibration of the test systems?*

- *What are the obstacles for implementing automation solutions in a production environment with intricate processes?*

1.5 Sustainability and Ethical Aspects

When it comes to sustainability a common way to express what needs to be achieved in the world is the set of 17 sustainable development goals presented by the United Nations, as a part of the 2030 agenda [3]. This project especially connects to goals 8 (decent work and economic growth), 9 (industry, innovation, and infrastructure), and 12 (responsible consumption and production). Especially target 8.4, 9.2, 9.5, and 12.6. Target 8.4 focuses on enhancing resource efficiency in production and consumption, while target 9.2 underscores the importance of sustainable and inclusive industrialisation. Target 9.5 is connected to scientific research and enabling technological advancement in industrial sectors. Lastly, 12.6 is connected to encouraging sustainable practices within large companies. These three sustainable development goals align with the sustainability strategy of Saab. Furthermore, a model called the triple bottom line can be used to explain three main areas of sustainability, economy, society, and environment [4]. Through this project, there were multiple connections to all three areas with varying degrees of impact.

There are a couple of relevant aspects that were taken into consideration during this project. The aim was not to create a solution that would displace the jobs of the operators who perform the calibration today, but rather to help them avoid the repetitive work so that they can focus on other tasks that require human supervision or add more value. It is therefore anticipated that this project could result in an improvement in the working environment for operators, while also increasing the availability of production. This could improve both the physical and mental well-being of the operators which in turn is hoped to have a positive impact on society.

When implementing automated solutions, it is also important to consider the ethical aspects. Saab produces radar units which are used for defensive, offensive, and security purposes. If these products were to fail due to errors in production, there is a risk of endangering human life and compromising the security of the operating country. An ethical aspect that needs consideration is the requirement for a clear liability in any eventually implemented automated system for some actor to bear responsibility if it fails.

Another ethical component of this work is research integrity. Research integrity reflects the presence of principles concerning honesty, accuracy, and transparency throughout the research process. These principles have been actively applied to ensure the project follows good research ethics. This is to ensure reliability and trustworthiness in both the project itself and its results.

1.6 Thesis Outline

This section presents the structure of the thesis.

Chapter 1: Introduction, presents the background for answering the research questions, the aim and scope of the project along with the limitations that were present. Furthermore, sustainability and ethical aspects are introduced.

Chapter 2: Theory, covers theory that is important to understand for the project. It covers topics such as automation, smart manufacturing, and Industry 4.0/5.0. Furthermore, it introduces collaborative robots (cobots) and discusses relevant aspects of these. It also covers theory regarding calibration.

Chapter 3: Methods, aims to explain how the study was conducted. It includes the literature study and current state analysis, including a qualitative study. The procedures for tests conducted during this project are also explained in detail here.

Chapter 4: Results from literature, is the first part of two within the results category that was created to capture the information that has been extracted from the literature search. It is particularly focused on automation technologies and collaborative robots.

Chapter 5: Results from Empirical Study, is a collection of the results from the tests performed and the current state analysis.

Chapter 6: Discussion, has the purpose of analysing the results of the tests, connecting them both to each other and to the application at production within Saab. Furthermore, this chapter includes concrete suggestions for Saab regarding the implementation of automation. The concluding section of this chapter presents the answers to the stated research questions and recommendations for further research.

Chapter 7: Conclusion, contains the key information of this project along with a reflection on the purpose of this project. The conclusion also comments on the analysis and implications of the results.

2

Theory

In this chapter, the theory that supports the understanding of this thesis is presented. This theory is useful for gaining an understanding of the subject area and as a foundation for answering the proposed research questions. The chapter covers relevant aspects regarding automation such as smart manufacturing, collaborative robots and the security aspects in this type of manufacturing system. The chapter also includes information on key performance indicatorw (KPI) and the basics of calibration.

2.1 Automation in Production

Automation is a broad term that could be described in many different ways. The authors in [5] state that automation is "the execution by a machine agent (usually a computer) of a function that was previously carried out by a human", which captures the essence of automation in modern manufacturing. Automation is a way for companies to increase their efficiency, which was one of the reasons why companies began automating decades ago [6]. Additionally, the authors mention that as automation evolved, it became evident that numerous parameters, such as quality and throughput, could be significantly improved through automation [7].

The concept of *levels of automation* (LoA) is a way to describe where a process is on a scale between fully manual and fully automated, regarding how it is carried out. There is no widespread scientific consensus on what type of levels or how many levels should be included in this scale, but many of the models are similar and include steps that coincide with each other [8]. This is essential to remember as comparing LoA evaluations from different scales could give a biased opinion of how automated a system is. Further discussed by [8], there are differences between autonomy and automation. The article highlights that there is an inability of previous scientific works to distinguish between autonomy and automation. They are often used interchangeably, as they are similar concepts, even when the authors know the difference between the concepts. Automation is when a process previously performed by a human is automatically controlled and executed [9]. Autonomy however can be described as a more intelligent system that can observe and analyse its environment and the data it receives and use this to plan and take action. This opens up to a broader spectrum of operations where the automated solution for example can be presented with situations it has never seen before and effectively solve these [9]. Some challenges when mixing these terms could be a mismatch in the expected capabilities of the solution or difficulties in implementation.

2.2 Smart Manufacturing

Manufacturing is a core part of many businesses. The term Industry 4.0 was originally introduced at the Hannover Fair in 2011 [10]. Smart manufacturing encompasses a range of key elements, including vertical integration, virtualisation, automation, traceability, flexibility, and energy management [11]. These constitute a fundamental aspect of Industry 4.0. An interesting find by [11] is that smart manufacturing technologies are complementary for companies to grow their Industry 4.0 maturity. This means that using a selective implementation of the technologies is not effective in comparison to many of them synergizing for a smarter manufacturing system.

2.2.1 Industry 4.0

Industry 4.0 builds upon many emerging advanced technologies working in unison to provide a smart structure of integrated systems that aim to provide added value for several aspects of businesses [11]. A part of Industry 4.0 is smart manufacturing, which includes two dimensions that were key for this project; automation and flexibility [11]. One of the core parts of Industry 4.0 is cyberphysical systems. These integrate computers and the equipment in the physical world which means that software and physical components interact with each other in multiple ways to create more intelligent systems [12].

2.2.2 Industry 5.0

With an expanding focus on people and the planet there has been a strive for a new industrial era, Industry 5.0, which has its roots in Industry 4.0. Industry 5.0 is based on three core principles [13]. The first principle is that production should be **human centric**, meaning that the people are the core of the process. For example, technology should be used to fulfil the needs of the people rather than having people conform to new technology. The second principle is that the industry or production should be **sustainable**. Some examples of sustainability are minimising waste, improving resource efficiency and using recyclable materials. The third principle of Industry 5.0 is the **resilience**. This means that parts of businesses such as processes and supply chains should be robust in a way that makes them less affected by factors like geopolitical situations, natural disasters and other disruptions. One of the fundamental aims of Industry 5.0 is to not prioritise profits but rather these three core principles [10], [13]. Both of these authors also connect cobots and safety to the human-centric principle of Industry 5.0. The authors of [14] present three ideas about Industry 5.0 and Industry 4.0 interacting. The first is that they could co-exist, meaning that Industry 5.0 will complement Industry 4.0 and that they will work together to intertwine with people and technology. The second is that Industry 4.0 will transition into 5.0. The third idea is a hybrid of 4.0 and 5.0, and they both have more in common than what you would expect. Thus, making it possible to recognise future smart factories as both Industry 4.0 and Industry 5.0.

2.3 Collaborative Robots

For Industry 4.0 and Industry 5.0, cobots are a technology that can be useful for moving towards enabling factories to work smarter [11], [15]. Cobots differ from traditional industrial robots and there is not generally a clear line drawn between them [16]. Multiple definitions explain what a cobot is. One example is; *"A "cobot" is a robotic device which manipulates objects in collaboration with a human operator"* [17], and a more modern one is; *"Cobots are industrial robots specially designed to work in close contact with people"* [18]. Some of the aspects that inherently make a cobot safe to use around humans are the multiple safety aspects that usually are included. Examples of these are that they are lightweight, have mechanisms for controlling velocity and range, and have rounded edges [19]. Standard industrial robots do not have these features to the same extent, which often means that you have to create physical safety barriers between them and the operators [19].

The extent to which an operator's tasks are in collaboration with a robot can be defined through five different levels of collaboration (LoC), which can be seen in Figure 2.1. In the literature, it is described that a *Cell* is when the cobot is fenced off from the human and that they do not share any space [19]. *Coexistence* means that the human and robot work beside each other but do not share a working area. *Synchronisation* is the method where the cobot and human share their working area, but they do not operate within it at the same time. *Co-operation* is when the human and the cobot are working in the same area simultaneously. *Collaboration* is when a robot and an operator share a working area and work on the same object together concurrently.

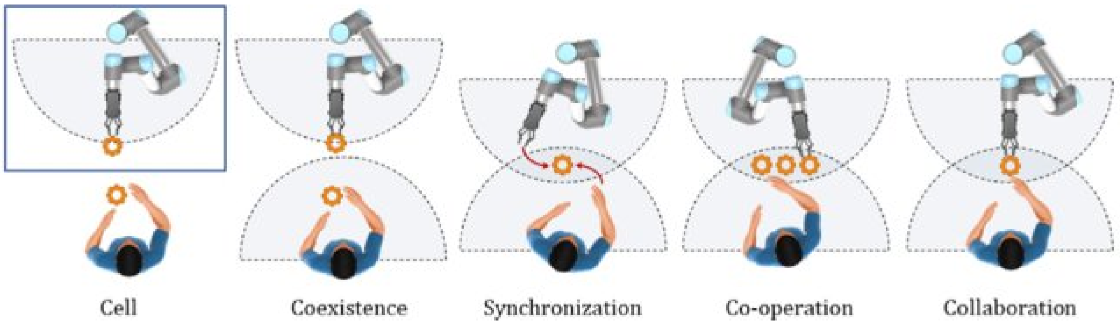

Figure 2.1. Level of collaboration for Cobot-human interaction[20]. Reprinted with permission.

In industry, there are new requirements that industrial robots cannot meet, but collaborative robots can. Some of the key factors to take into consideration when implementing cobots are operator safety, training of operators, workplace layout and selection of peripheral devices [21]. When designing a process, it is important to keep in mind that cobots have technical limitations that may affect their efficiency in certain tasks. Therefore, it is necessary to identify tasks that are suitable for cobots while considering the listed key factors.

Compared to the programming of traditional industrial robots, the requirements are lower for programming cobots. An experienced programmer is often needed to program an industrial robot and it takes time to change the robot's tasks [22], [23]. A cobot can be programmed by moving it with your hands, and it has an interface adapted for humans [22]. It is also possible to program it more traditionally, resembling the programming of an industrial robot. The importance of having a user-friendly environment is well-researched and the latest focus in research has been on visual programming, with block charts or similar. Visual programming is becoming a standard programming method for the programming of cobots [24].

2.3.1 Robot Performance

The accuracy of the robot can be affected by the payload and external forces. The external forces often come from the performed operation by the robot [25]. Due to cobots' reconfigurability, such as ease of moving around in production, calibration of cobots needs to be done frequently. For industrial robots and cobots, their repeatability is usually their strength while absolute accuracy is worse. Furthermore, the lightweight construction of cobots and their common placement on mobile workstations can result in them being moved by accident. Therefore precise calibration must be performed, which makes it possible to utilise the good positioning repeatability of a robot and ensure that the robot accurately hits the targets [26].

The calibration of the robot can be done in the robot's joints, the equipment, and the robot-user frames [26]. A reference coordinate system, often called a user frame, is calibrated through the relation of the workpiece with respect to the base coordinate system of the robot. The user frame coordinate system is often a more intuitive choice for operators, as it remains consistent regardless of the position of the cobot. The user frame will be a fixed reference system and the robot positioning and configurations are changed according to that. This means that the process is dependent on the relation between the two coordinate systems. If either the robot or the user frame is moved slightly it leads to the robot's performance being impacted and might lead to process failure.

Two commonly used methods for calibration are mechanical methods and vision-based methods [26]. Mechanical methods are the most commonly used method within robotics and it gives the most accurate calibration. Usually, the robot is moved to markers or reference points in the user frame. According to the authors, for applications requiring high accuracy, external sensors such as proximity sensors or lasers may be used. These sensors measure the distance between the sensing points and the robot tool. Further discussed by [26] is that vision-based methods often achieve a lower accuracy, but are instead faster than mechanical calibration methods. Many computer-based algorithms use vision to extract information used for vision-based calibration.

2.3.2 End Effectors and Fixtures

End effectors allow the robot to perform specific tasks and are often designed with a particular function in mind. Grippers, process tools and end effector exchange systems are subgroups of end effectors [25]. End effectors significantly affect the performance of the robot, for example, accuracy and workplace throughput [27]. When selecting an end effector, it is generally advisable to choose a simpler design that can effectively perform the task rather than opting for a more complex one with multiple functions [25].

Grippers are commonly used in assembly and material handling tasks. The most common types of grippers operate using mechanical, vacuum, or electromagnetic methods. The gripper selection is affected by several parameters including weight, geometrical size, contact force and contact surface, accuracy and repeatability, and environment and robustness [25]. The weight of the gripper affects the abilities of the robots while the capability to reach a point from different orientations is impacted by the size and design of the gripper. These two factors can also impact collision risks with other equipment. The required gripping force is affected by various parameters of the grasped object, including its shape, weight, and friction. Additionally, the object may have other limitations that affect the contact force such as a sensitive surface. It is also important to consider environmental factors such as humidity and temperature in the selection process of the gripper. For collaborative applications, the selection or design of a gripper needs to include human factors [28]. Depending on the level of collaboration it needs to follow ISO standards, for example, it can not have any sharp edges.

Mechanical grippers often consist of two or three fingers/jaws [25]. Two-finger grippers are the most basic grippers and also the most common. These grippers are commonly used for assembly, pick and place, and simple manipulation. Two-finger grippers are more frequently used as they usually meet the requirements of the task. However, three-finger grippers may be more suitable for handling fragile objects or when greater accuracy is required [29]. Some mechanical grippers are more flexible and resemble human fingers and hands. However, it is recommended to use them only when there are no other reasonable alternatives [25]. The authors of [25] mention that sensors can be utilised to determine whether the gripper has grasped an object. The sensors provide information on the state of the gripper, indicating whether it is open, fully closed, or in a middle position.

The clamping force of mechanical grippers is generated by either pneumatics or electricity [30]. Electric grippers use motors to control the moveme nt of the fingers, providing ease of control over both position and speed. It is stated that for high-precision assemblies, servo motors are ideal. Servo motors are preferred in applications that require sensitive positioning and force. It is also preferred for lighter loads. Pneumatic grippers are a type of linear actuator that often allows for faster direction changes. They are thereby commonly used in industrial robot applications when a large force is required.

Vacuum grippers are commonly used for grasping objects that are challenging for mechanical grippers to handle. These objects may be sensitive to the gripping force or have an odd shape. It is common to use vacuum grippers for objects with flat surfaces [25]. The flexibility and good grip make vacuum grippers advantageous [29]. A sensor can be used to measure the vacuum level and determine if the gripper has picked up the object [25].

For tools used by robots, it is necessary to define the Tool Center Point (TCP). This is to facilitate robot programming and be able to move the correct part of a tool to the desired coordinates. The TCP is defined in a Cartesian coordinate system and can be defined through different procedures [25]. It can be calibrated by moving the attached tool to the same point but with four different robot configurations. The accuracy of the TCP depends on the accuracy of the positions that were used when calibrating the TCP. There is also the possibility of using data of the tool dimensions directly but it requires that the tool has been measured and manufactured accurately and precisely.

Another important aspect of the mechanical design of a workstation is fixtures. A body has six degrees of freedom, meaning it can move freely along three linear axes (x, y, z) and also rotate around them. A fixture holds an object/workpiece firmly during manufacturing operations [31]. The fixture constrains the degrees of freedom of the workpiece. If any degree of freedom is unconstrained the object will be under-constrained [32]. Ideally, a workpiece is well-constrained when six locating points restrict all degrees of freedom, making this the optimal configuration for fixture design. Nevertheless, if the fixture constrains the workpiece in more degrees of freedom than necessary, it becomes over-constrained. Over-constraining can lead to deflection of the object and compromise repeatability.

2.3.3 Vision

Various types of cameras are used in vision applications. These cameras differ in numerous technical aspects from one model to another. For instance, a camera system might be classified as either 2D or 3D, equipped with integrated processing technology, built-in lighting, and infrared capabilities, all tailored to suit its intended function. One example of how to apply this technology is for use in automation, specifically along with cobots to perceive their environments, as done by [33]. This is one of the reasons why vision is of interest for this project.

Vision-based cobots for grasping are an extensively researched topic in both academia and industry. Deep vision technology can accurately locate targets and predict their angle and width. There are few methods available for simultaneously identifying objects and predicting grasping [34]. Usually identification of objects is visualised with bounding boxes, like in Figure 2.2.

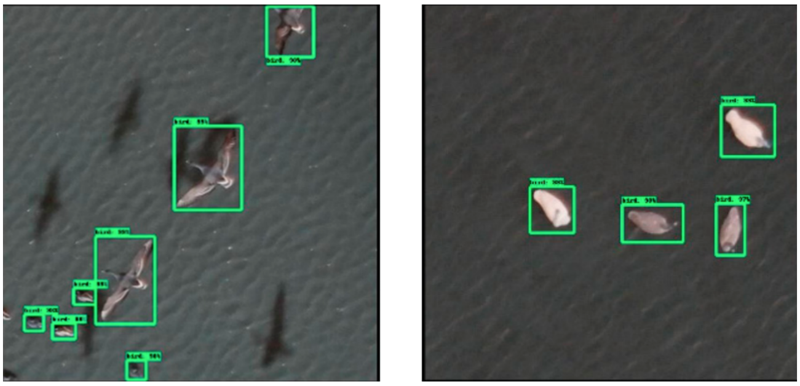

Figure 2.2. Green bounding boxes to visualise object detection of birds using deep learning [35]. CC-BY.

For vision systems paired with cobots a common technique for localisation is fiducial markers [36]. Some popular variants are ARTag, April, ArUco and STag [37]. They all exist for similar purposes which are to be detected by a computer system equipped with a camera and be used for localisation or tracking [37]. Although their purpose is similar, there are many variants to choose from and they all offer different benefits and detriments such as varying computational costs and detection rates. Higher resolution cameras do not always have the best detection rate and performance [37]. The performance depends on multiple factors such as contrast, edge smoothing and white balance.

2.3.4 Machine Learning

To make vision systems smarter and more useful they are often combined with machine learning algorithms. YOLO is one type of deep-learning network that is commonly used for object detection. This network is relatively simple to train, offers object detection, and is open source [36]. There are many different versions of the network, for example, the YOLO-LITE which performs well for live-detection and has low computational costs [38]. The article by [39] presents some of the improvements from the traditional YOLO V1 to the YOLO V5 model such as performance and user-friendliness. As of 2023 the most recently released model is the YOLO V8 [40].

Another example which could be used is the EfficientDet model [41]. It utilises a new architecture in combination with a scaling method. The scaling method adjusts the model so that it can work well for different processing capacities, ranging from model D0 to D7. Single Shot MultiBox Detector is another popular alternative [42]. This method uses a feed-forward convolutional network to produce bounding boxes and scores for the different objects that need to be identified.

2.3.5 Sensors

Industrial and collaborative robot systems usually make use of sensors to monitor the state of the system and to receive information about the environment in which they work. The sensor signals are used by the control system to, for example, know what the next step in the process is and if it is safe to execute. There is a wide range of different sensor types with different application areas. Some examples are inductive sensors, photoelectric sensors, load sensors and vision sensors (presented in Section 2.3.3). These different types of technologies had to be considered during this project to evaluate if any of them could be useful for the case in question.

2.3.6 Safety Requirements

ISO standards are developed to establish safety requirements for robots, ensuring that they do not harm operators or equipment. ISO 10218-1:2011 was developed for industrial robots [43] and in 2016, ISO/TS 15066:2016 was published for cobots to supplement the older standard [44]. ISO/TS 15066:2016 is rooted in ISO 10218-1:2011. Several factors are presented to eliminate hazards and reduce risks. The list includes access, clearance and limits of the collaborative workspace, human interface, ergonomics, use limits and, transitions. Transitions between collaborative and non-collaborative operations are a critical part and must be designed so that the operator is not exposed to unacceptable risks during the transition.

The collaboration between humans and robots is enabled by safety-rated methods. Four methods are presented and the application can have one or more of these methods [44]. Safety-rated monitoring stop is one method and it means that the robot will stop working if a human enters the collaborative workspace. Another method is hand guiding which means that the robot makes a safety-rated monitored stop before it enters the collaborative workspace. The operator can then take control of the robot with a hand-guiding device to perform the task. If the device is released by the operator the stop is activated again. If the operator has left the workspace the robot can continue on a non-collaborative task inside the collaborative workspace. The third method, speed and separation monitoring (SSM), allows the operator and the cobot to move at the same time in the collaborative workspace. The cobot always maintains a distance from the operator, called the protective separation distance. The cobot should never get closer than this distance, and if the distance becomes too small, the cobot will stop until it is the right distance again. Power and force limiting is the fourth method. Intentional or unintentional physical contact between the operator and the cobot system (the workpiece is included) can occur which is sensed by the robot. The robot can then limit the force it exerts to avoid injuring the operator or damaging equipment, which means that this method enables collaboration. A cobot equipped with this method must be designed so the force or pressure between the cobot system and the human never exceeds the unacceptable region. The ISO standard presents a list of the limits for body regions.

2.4 Security Risks in Smart Manufacturing

With Industry 4.0 and smarter factories comes the inevitable usage and management of data or information. According to [1], this can be problematic for businesses if cybersecurity is overlooked. They mention that it can lead to competitors gaining valuable information from your business which can give them a competitive edge. Hackers can disrupt manufacturing operations causing you to lose money or customers and security systems might be targeted endangering the safety of both operators and customers. For a business like Saab, it is essential to ensure that safety is a key priority. If information gets into the wrong hands it can jeopardise the safety of large amounts of people, not only in Sweden but worldwide. The article from [1] describes that cyber-attacks can be both internal and external sources which is also an important aspect to consider. Further on it is pointed out that the cybersecurity systems have to be updated continuously at all levels from device, up to company level to avoid protection becoming outdated.

2.5 Calibration and Signals

Calibration can be explained through three concepts; accuracy, precision, and uncertainty. These three parameters are used to explain how a measured value relates to the actual true value of the parameters measured [45]. Further mentioned by the literature is that calibration is often done by using a known reference point which makes it possible to know how well the equipment performs. Calibration is essential for multiple reasons. Performing calibration is a way to ensure that the equipment performs how it is supposed to, within its specified limits [46]. It is also a way to make production safer through ensuring that the equipment does not fail and that the quality demands of the products are met [45]. On top of this, calibration is a way to make sure that the equipment stays within industry standards, such as the ISO/IEC 17025 that is used for testing and calibration laboratories.

The electromagnetic spectrum contains multiple classifications of electromagnetic energy, of which only a small part is the visible spectrum [47]. The authors present two types of available categorisations based on frequency bands, such as from the International Telecommunication Union where some examples are high frequency (3-30 MHz) and low frequency (3-30 kHz). Furthermore, they mention that The Institute of Electrical and Electronics Engineers also categorise types of frequencies in a section of the electromagnetic spectrum, more used for technology like radars and satellites. Some examples of these are the L band (1-2 GHz) and the S band (2-4 GHz).

Saab uses equipment that operates within radio frequency (RF) and microwave frequencies. The RF path between the tested product and the test instrument contains switches, cables and components, which all decrease the measurement accuracy because of losses when signals pass through the equipment. Losses can occur in multiple types of signals. Radio wave and microwave frequencies are commonly used when working with radars, but losses can also occur in electrical signals such as in direct current. The accuracy loss when using RF signals can be characterised and corrected through calibration [48]. The calibration method for correcting the errors can either be vector or scalar. The selected method depends on the RF signal path and type of measurement. Phase and gain measurements of the RF path need vector calibration while only the magnitude of the RF path can be characterised by the scalar methods. This means that the scalar calibration does not give a complete characterisation of the path.

A power meter, a signal generator or a spectrum analyser are often used for the scalar methods [48]. One common approach is to drive the end of the path with a signal generator and use a power meter to measure the signal at the other end. The source power setting is subtracted from the measured power level and this way the magnitude of the path response can be obtained. The overall magnitude characteristic is determined by repeating the process for many frequencies.

The vector calibration method can be done by calibrating the ports of the device that is being tested by using a network analyser [48]. Another presented approach is to measure the scattering parameters of the RF path by using a network analyser. Scattering parameters describe how a component modifies an applied signal.

Calibration is needed when something in the system changes. This means that if a test fixture or components used in the station are changed, it affects the calibration and a new one might need to be re-done. Other areas that affect the characteristics are ageing materials, wear of the connectors and the drift of the components in the system [48]. Calibrations thereby need to be done regularly and a calibration schedule can be decided by analysing the calibration data over time. Setting a replacement schedule for frequently used connectors is also beneficial since the system needs calibration when an RF component is replaced. Calibrations at Saab can be divided into two different types of calibrations called Tier-1 and Tier-2. Tier-1 is done more frequently and when a Tier-2 is done, a Tier-1 also needs to be done.

RF components need to be handled carefully. Bending a coaxial cable should be avoided because it can affect the impedance of the cable and higher frequencies are more sensitive to this type of disturbance.

2.6 Key Performance Indicator

For manufacturing industries, there are several ways to measure how well the production system is performing. A standardised system, ISO 22400, has been developed for KPIs to have common ground for several common KPIs used in businesses for performance evaluation [49]. Some examples of these are overall equipment efficiency index, quality rate, throughput, availability, and efficiency.

3

Methods

This chapter presents how the thesis was conducted and the reasons for the selected methods. The work is divided into three distinct steps: literature study, current state analysis, and cobot tests of calibration tasks.

3.1 Literature Study

A structured literature study was conducted to develop a better understanding of the topic and to provide a basis for answering the research questions. The research databases IEEE, Scopus, Google Scholar and Semantic Scholar were primarily used for finding literature. The literature study followed guidelines for systematic review, presented in [50] and it was complemented with the systematic methodology called snowballing described in [51]. The first step was to identify keywords. Examples of identified keywords were, Automation, Production, Robot, Cobot/collaborative applications, Vision, AI, Machine Learning, Gripper, and Cable. Filtering was done by including articles from the last seven years, which were then sorted on the number of citations. The reason for filtering out articles older than seven years during the literature study was to ensure that the review was based on the latest trends and state-of-the-art research. The relevance of each article was judged through analysis of its abstract, and only relevant articles were read through and fully analysed. This process is illustrated in Figure 3.1.

The iteration process called backward snowballing, see Figure 3.2 was done on the 14 fully analysed articles which includes looking at all the titles in the reference list. Titles in languages other than English, already-used articles, and articles that seemed irrelevant (based on the title and its use in the examined article) were excluded from the iteration process. The remaining articles were analysed by reading the abstracts and browsing through the papers. Forward snowballing is another used methodology where instead new articles were identified by finding papers that have cited the examined paper. The new papers were selected by the same methodology as backward snowballing. The reason why this was deemed a useful method in literature search is due to the exploratory nature of this project. One key point of the literature search was to explore how other researchers have tackled similar problems and then dive into the technology that they have used. Therefore it was of great value to investigate information from the sources used in other articles as well to see if it could be useful for this project.

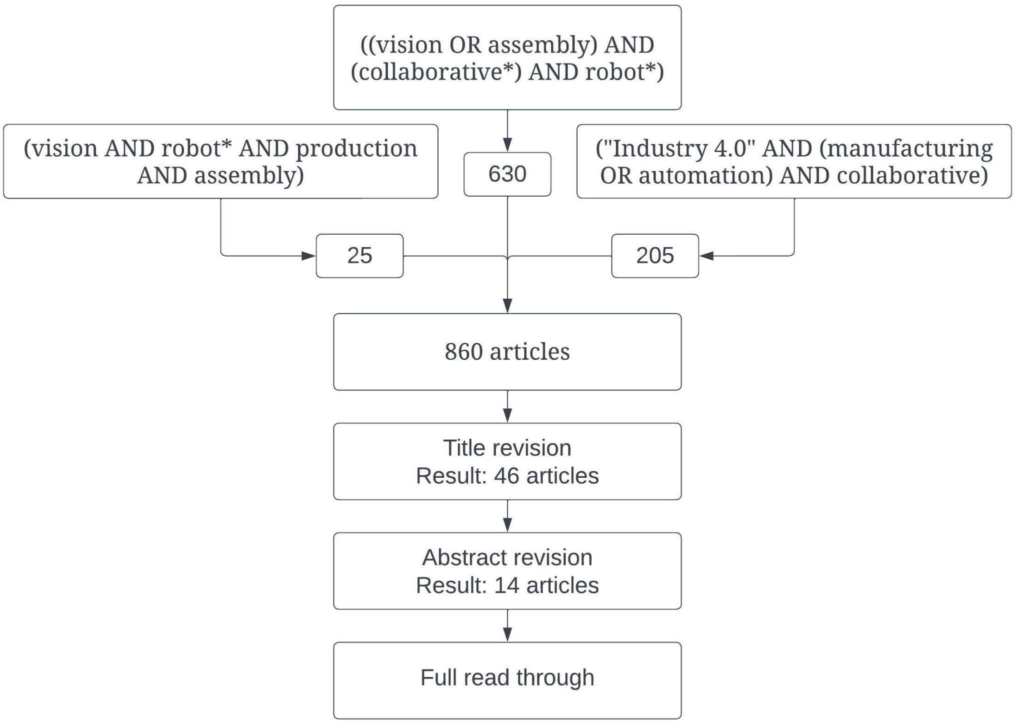

Figure 3.1. Process for literature study.

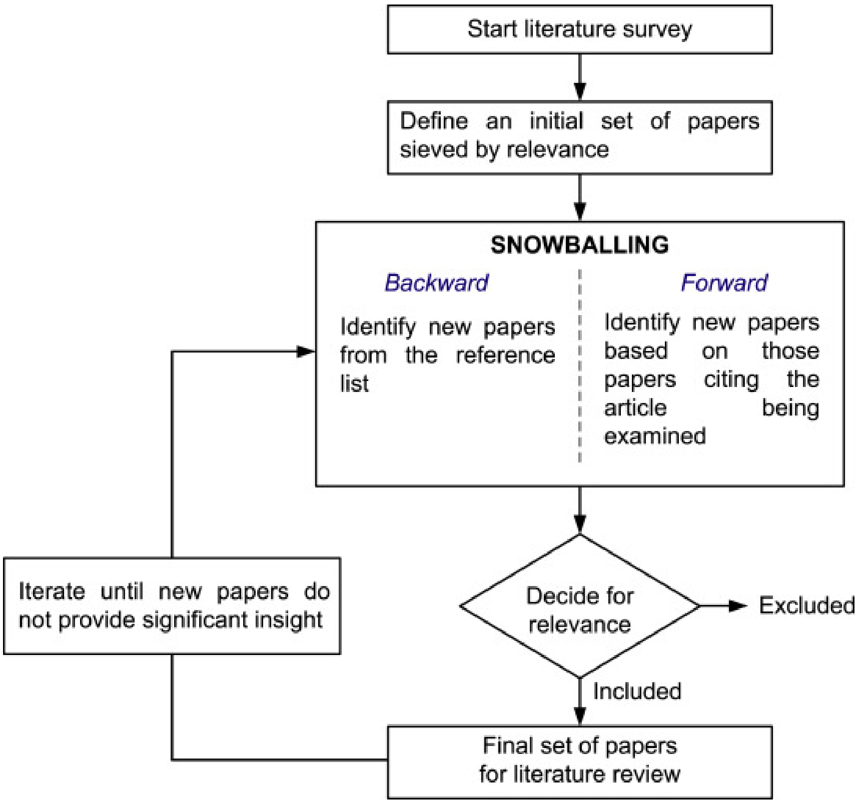

Figure 3.2. Snowballing process used for literature study. [52], CC BY-NC-ND 4.0

3.2 Current State Analysis

A current state analysis (CSA) was conducted to examine the current calibration process. This was done to gain insight into the strengths and weaknesses of the current processes. Through knowing the current state, it is possible to compare it to an automated solution and evaluate if it would be a worthwhile investment. Additionally, the analysis can help to identify the requirements for an automated solution. This type of analysis required extra effort due to the project being conducted in parallel with the implementation of the new production line, in which the results of the project were to be implemented.

The CSA followed a qualitative research approach. A qualitative study is a study which is focused on understanding complex topics through detailed analysis of non-numerical data. Instead of focusing on quantitative results it rather serves to explore context and observations which are not easy to categorise and put into numbers [53]. The reason why this type of method was useful for this project is because observations were taken from multiple stations of different designs and were complex to categorise.

Interviews and observations were conducted in three different test stations, where different products are handled and that includes dissimilar process steps. Interviews were conducted with the operators while the calibration process was done for these three stations. Observations were noted, for example, process steps, difficulties and tools used. The interviews followed a semi-structured format, with some questions decided beforehand and then follow-up questions were used based on what the operator answered or did in the process.

Before the interviews, some calibration instructions for the operators were reviewed. This was done to facilitate questioning and to create a list of what to observe. The used questions and list of observations are presented in Appendix A. For the CSA the Level of Automation (LoA) of the current process was also determined to be used as a reference point and to describe in which state the calibration process currently is within. The reason for this is to also have a starting point to build upon when determining what LoA is a reasonable level for Saab to aim for as a step in their automation journey.

Approximated cycle time measurements were performed on some of the calibration processes as a part of the CSA. The requirement for a process to be measured was that it had the potential to be tested with a cobot or that it was similar to the one that will be used in the new production line. The reason for the time measurements was to enable a comparison of the performance between the tested concepts and an operator. To determine which tasks should be measured, the processes were observed once before the cycle time measurement. The calibration process was broken down into tasks, where each task was measured and noted.

It was also important to know how the future Smart Factory will look like since it affects the design of the calibration process. The project of Smart Factory was ongoing in parallel with the thesis. Questions were raised to supervisors regarding the design of the test stations and meetings were attended to gain information regarding the latest updates. This information was essential to the decisions made during this project as the automation will take place in the Smart Factory.

3.3 Test Design and Procedure

This section will outline the procedure for testing and developing equipment for the tests.

3.3.1 Strategy for Test Design

The aim was to develop conceptual solutions for automating the key areas identified during the CSA. The selection of tests was based on steps identified during the CSA but also to investigate what the literature could not give a clear answer to. The reason for developing the tests was to collect evidence about the degree of feasibility, and how availability and quality could be expected to change for similar solutions when deployed in a production environment. It is also a way to prove how a cobot can be useful for performing these tasks and making sure that the robot can handle the precision and accuracy that is needed, which will be important when determining the value of an automated solution.

The number of repetitions for the contacting tests was made by determining the average number of ports calibrated and the number of calibrations made per day. Furthermore, a safety factor was added on top to take into account any uncertainties. On average it was assumed that a maximum of three calibrations would be done per day, meaning one calibration per shift if operations are run 24 hours per day. The number of ports calibrated on average for each calibration, determined from the CSA, was 25. The average amount of repetitions per shift is therefore approximated to be 25, as of now. This number is generous and takes into account an increase in the calibration frequency which can be expected.

The robot used for the test was Universal Robots' UR3, while the robot at Saab is a UR5e. A pneumatic gripper was used for all the tests as it was the only type available. The fingers on the gripper were designed specifically for each test to grip the cable/connector. The fingers were 3D-printed in micro carbon fibre-filled nylon, a material called Onyx from Markedforged. The fingers were mounted on the parallel gripper Konex P50 from Schunk which has a stroke length of 5 mm per jaw. The system operated at a maximum pressure of 6 bar. The robot was online programmed, meaning that the robot was jogged to the wanted positions and all locations were saved to form a movement sequence.

For all of the tests, two people were watching at all times to observe errors and performance. Many of the tests include a performance factor denoted as success rate, which is the ratio between successful and total attempts at a task. If the robot failed any task in the cycle, the robot was paused and the test equipment (cables and robot) was moved back to its starting position, and a new cycle was initiated.

A test rig containing different connector types was assembled for the tests, see Figure 3.3. It had a similar interface to the ones used at the calibration at Saab. The test rig was fixed in place within the robot's workspace and clamped to the table to prevent movement.

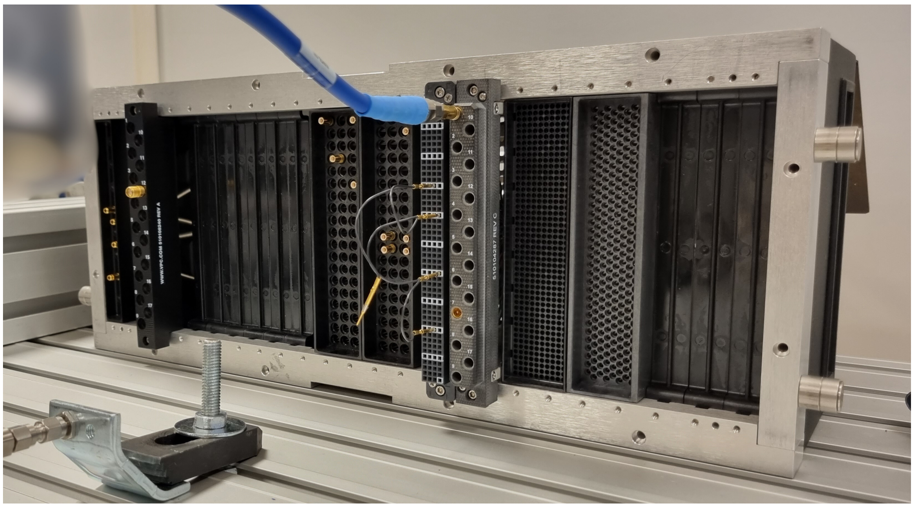

Figure 3.3. Interface that was used for Test 1, 2 and 4.

When all of the tests had been performed the results were compiled and evaluated. Together with the CSA and the literature, the test results were used to analyse how automation solutions are expected to impact the calibration operations at Saab and what technologies could be suitable for this specific case.

3.3.2 Test 1 - Insertion of Coaxial Cable with Adaptor

The first area of focus for concept development involved solving a precision task using a coaxial RF cable with an adaptor attached to it. This adaptor essentially turned the cable into a slide-on contact. This test was done to resemble one type of contact that could be present in the interchangeable test adaptor (ITA) or automated test equipment (ATE) interfaces. This test resembled one of the observed cases at Saab. The type of contact can be seen in Figure 3.4 and the type of socket can be seen in Figure 3.5.

The robot was programmed to pull the contact out of one slot, put it into another and then release it. Then it fetched it from the second slot and put it into the first slot. This was defined as one cycle, meaning that each cycle contains two grip actions and two inserting actions. This cycle was repeated 75 times, with variation in cable positions induced after 50 cycles. This means that 150 contacting actions were performed.

Figure 3.4. Coaxial RF cable of type SMA with an attached adaptor for slide-on connections. This type of contact was used in Test 1. Diameter of gold tip ≈ 3.5 mm.

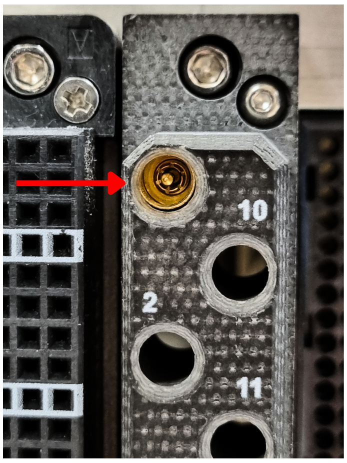

Figure 3.5. Type of socket used for Test 1. Diameter of socket ≈ 4.00 mm.

To introduce another type of variation into this test, the position of the cable end not gripped by the grip was altered. This adjustment mimics scenarios that could be expected to happen during calibration as it is not certain that the location of the other cable end will remain constant. During this test, it was also relevant to vary the angle of the contacting since this type of environment is expected to be present in the new production line. Testing different angles gave the test another type of variation. These tests were run with angles of ± 40° from the horizontal plane, see Figure 3.6 and Figure 3.7. For each of the setups, 25 cycles were run resulting in 50 cycles and 100 contacting attempts for the angular testing. This means that the total amount of contacting attempts performed for the entire Test 1 was 250.

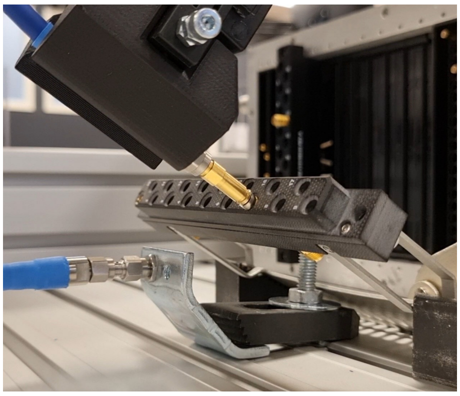

Figure 3.6. Variation of Test 1 at 40° positive angle from the horizontal plane.

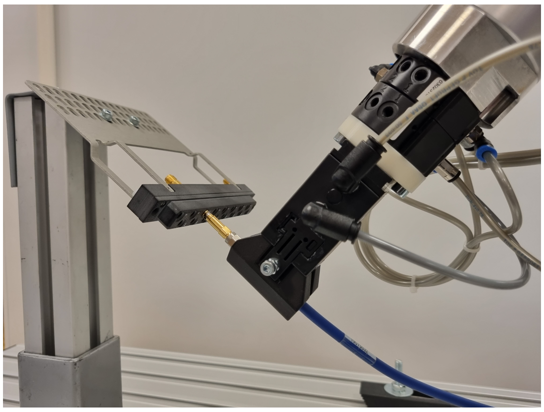

Figure 3.7. Variation of Test 1 at 40° negative angle from the horizontal plane.

3.3.3 Test 2 - Insertion of QuadraPaddle Contact

This contacting test resembles another one of the types present in the ITA and ATE interfaces. The type of contact can be seen in Figure 3.8 and the type of socket can be seen in Figure 3.9. This type of contact is not as common as the RF cables when working with the test system calibration. However, it can serve as an effective test for evaluating the robot's precision and its ability to handle small connectors.

Figure 3.8. Type of contact used for Test 2. Diameter of gold tip ≈ 0.6 mm

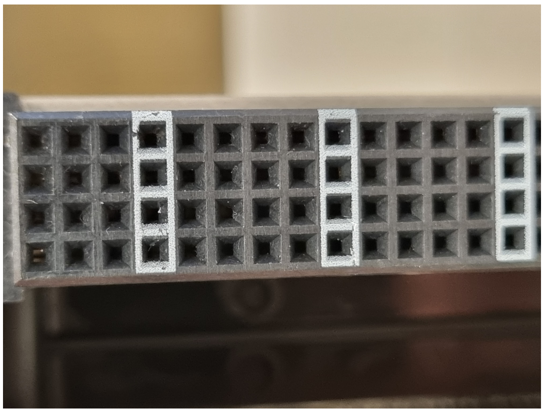

Figure 3.9. Type of socket used for Test 2. Side length ≈ 1.6 mm, including chamfer.

For Test 2, the robot program was similar to the one in Test 1. It pulled out the small connector from one socket at the top, put it in another, and released. Then it grabbed the connector from the second socket and put it back into the first socket. This test was repeated 60 times, with variation introduced after 30 cycles. A total of 120 contact attempts were made.

For this test, the variation was induced by changing the applied air pressure in the pneumatic gripper. The first 30 cycles were run with 3 bar while the other 30 were run with 2 bar of pressure. The pressure change was meant to replicate fluctuations in the pneumatic system and see if grip strength affected performance as the gripping surface for this type of contact was smooth and potentially lacked friction.

3.3.4 Test 3 - Coaxial Threading

In this test the possibility to connect a threaded coaxial RF cable (male) to a socket (female) with an automated solution. The test was done from an exploratory point of view as these types of connections were commonly observed in the calibration operations, and no already invented solutions were found. This test was designed to solve a process where the operator had to manipulate up to three objects at a time, which could be challenging for a robot. The three objects were a torque wrench, an adaptor and the RF cable which were used in different combinations. Also, the cables use threaded connections which adds another layer of complexity for eventual solutions. The cable type can be seen in Figure 3.10. As this test was exploratory it did not include any repetitions but resembled a product development and idea generation intending to solve the task.

The procedure consisted of generating different mechanism ideas that could solve holding the cable at the same time as rotating the nut at the end of the cable. This mechanism was intended to be implemented in a gripper if successful in performing the task. This test was therefore not a repetition test but rather a creative experiment focused on generating conceptual ideas.

3.3.5 Test 4 - Coaxial Slide-On

Test 4 is similar to Test 1 but was instead done with an adaptor attached to the threaded coaxial RF cable which essentially made it a slide-on connector. The contact can be seen in Figure 3.10 and the type of socket can be seen in Figure 3.11.

The test was performed by picking up the cable from a connector, mounted on a bracket away from the contacting interface. It was then put back in the same connector once and picked up again. This was done to spot errors in the initial pick action. Then the cable was placed on a similar connector type mounted on the interface. The cable was then placed back on the initial bracket. This test was run for a total of 50 cycles, of which 25 cycles had introduced variation. Each cycle included three contact insertions, resulting in a total of 150 contacting attempts for the entire test. The reason for running fewer cycles was that this test had three contacting actions instead of two, resulting in the same amount of contacting attempts as Test 1. The cycle times were also significantly longer than for the other tests.

Figure 3.10. Coaxial RF cable of type SMA with an attached adaptor for slide-on connections. This type of contact was used in Test 4. Inner diameter of adaptor ≈ 6.40 mm.

Figure 3.11. Type of socket used for Test 4. Outer diameter of threads ≈ 6.25 mm.

The variation induced in this test was similar to Test 1, where the cable end not manipulated was oriented in varied positions for replicating variations that could occur. The cable was oriented in multiple ways during the last 25 test trials and the robot program was paused after each completed cycle to allow the cable to be placed in various positions.

3.3.6 Test 5 - Spring-Loaded Coaxial Probe

This test examined a type of female connector that was not present in the CSA, a spring-loaded coaxial probe. The connector type will be used in the new production line. The test involved inserting an SMP male adaptor into the spring-loaded female connector and probing multiple times. The main objective of the test was to investigate the precision of the probing and whether the robot could fully compress the spring.

The test was done by placing two connectors into two fixed positions in a 3D-printed fixture, see Figure 3.12. The design of the fixture resembled the cooling plate that will be used as a fixture for the product in the new production line. The inserting connector type was SMP and consequently, the corresponding SMP male adaptor was mounted on the coaxial RF cable. The gripper that was used in Tests 1 and 4 could be reused for this test. The cable was placed in the gripper and it was never released during the test. The robot was first programmed to approach one of the connectors and then probe it by pressing down on the spring-loaded female connector until it reached the required point, holding it for five seconds. The robot was then programmed to move to the second connector and repeat the process. The program was looped, and a total of 40 cycles were tested.

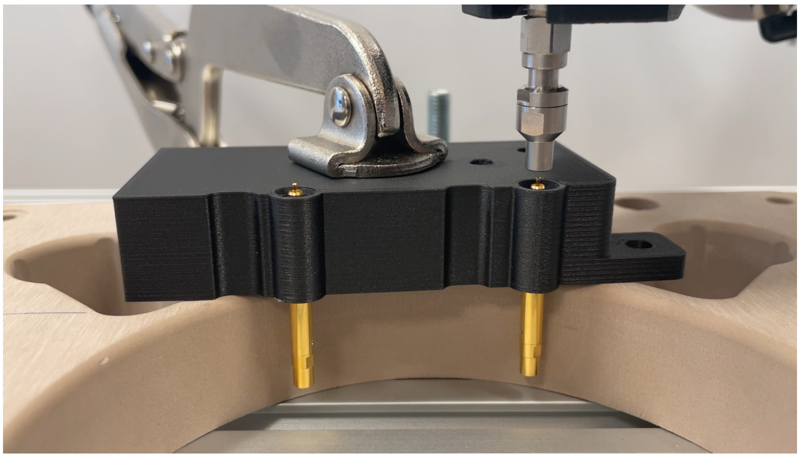

Figure 3.12. Setup for Test 5, containing 3D-printed fixture and two spring-loaded coaxial probes.

After 40 cycles, variation was introduced by relocating the spring-loaded coaxial probes to two other holes with chamfers on the edges. The robot was then reprogrammed to perform the same task but for the new holes. 40 cycles were tested for the relocated connectors, just like in the first part of this test. A cycle was considered successful if the SMP male connector made contact with the spring-loaded connector and pressed it down.

Testing different angles of contact was crucial because such variations are likely to occur in future calibration operations. Therefore, it was essential to ensure that the test results remained consistent across varying angles to draw any conclusions from the experiment. Because of this, two different orientations of the fixture were added as variations to the test. The fixture was first rotated at 140° and tested for 40 cycles. The fixture was then placed upside down, 180°, and was tested for another 40 cycles. Figure 3.13 and Figure 3.14 show how the fixture was oriented for the two cases.

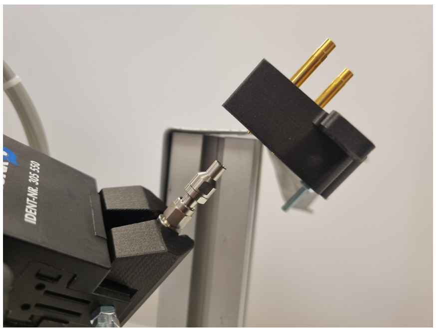

Figure 3.13. Variation of Test 5 at 140° angle.

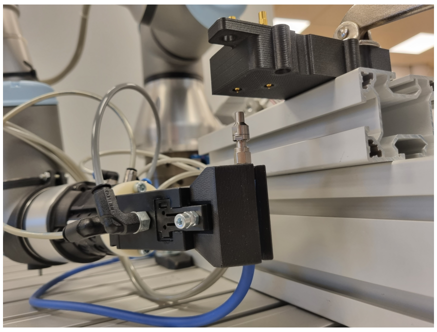

Figure 3.14. Variation of Test 5, in which the fixture was positioned upside down.

3.3.7 Additional Tests

During the testing, there were also a couple of smaller tests performed for evaluation purposes. One of these was to try programming the robot with coordinate systems as references even though this is not a built-in functionality of the UR3. This was done by measuring the TCP of one of the corners of the Schunk P50 and then using it as a measurement probe to gather six points of the desired coordinate system (the connection interface used for testing). These points were then exported as a script through USB and imported into a third-party program called RoboDK, used for programming robots. In RoboDK these points were used as references for defining the coordinate system. The reason for this test was to evaluate how reference frames impacted the performance, as reference frames are commonly used for robot programming but are not included in the UR3.

4

Results from Literature

In this chapter, the findings from the literature review and their relevance to this project will be discussed. A thorough analysis was conducted on 14 key pieces of literature, with additional sources identified through the snowballing method, see Section 3.1.

4.1 Level of Automation & Task Allocation

The literature presented a batch of taxonomies for the levels of automation that were suited for a range of applications [8]. For this particular case, two models initially appeared suitable: the model created by the authors in [8] and the model by Endsley and Kaber [54]. After some consideration, it was decided that another model designed with cobots as a central pillar would be more suitable to use since the models by [8] and [54] do not cover human-robot collaboration and could be outdated.

The concept presented by [55] describes a way of categorising tasks based on several parameters. The first parameters are regarding what level of cognitive and physical automation the tasks are classified as, see Appendix B. Secondly, the categorisation is based on the level of skill required (LoSr) including the five levels: **No skills**, **Foundational**, **Intermediate**, **Advanced** and **Expert**. Based on this the authors present examples of tasks which are categorised from their LoA (both physical and cognitive) to obtain a suitable LoC. This is then presented together with the LoSr to gain an understanding of the task and to efficiently be able to allocate tasks to humans and machines in a way that does not limit the involvement of either. The reason why the individual task, and not the entire process, is allocated with a LoA and LoSr is to not limit the extent to which an operator or robot can be involved in a task. Each task has different requirements for both the human and the robot [55]. Therefore, if an entire operation is classified as a specific LoA and LoSr it would not fully utilise the potential of human-robot collaboration.

4.2 Automation Technologies

One question that was raised during this project is: Why would companies use advanced technology for their production? Many different technologies affect both the KPIs presented in Section 4.4 but also flexibility, which is an important factor for Saab. Through flexible equipment, the cost per product can be reduced for low-volume production, see Figure 4.1. Flexibility, quality and availability can all be affected by different technologies. In this subsection, some of the findings for the studied technologies will be presented.

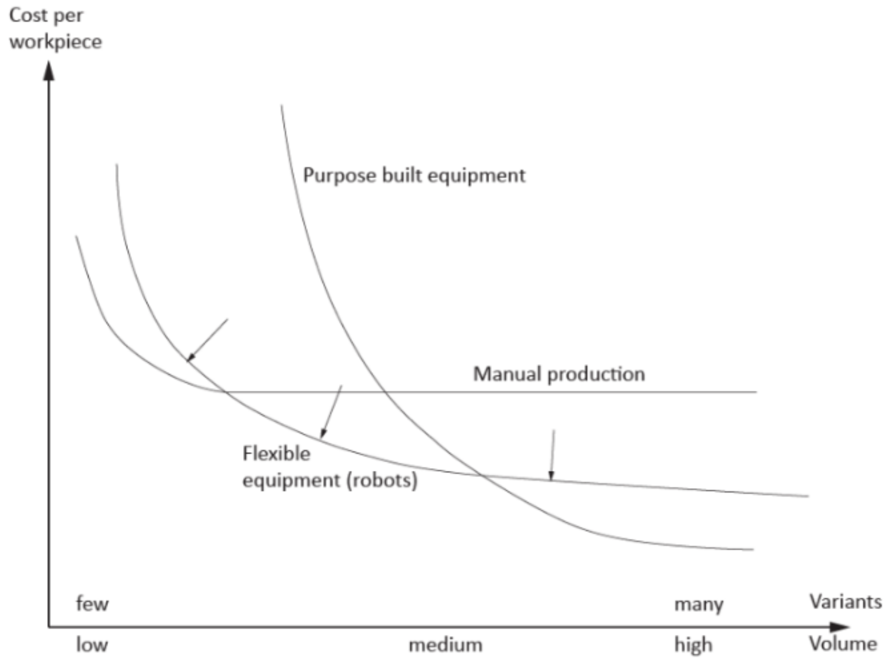

Figure 4.1. Comparison of use and cost per product between manual, purpose-built built, and flexible equipment [25]. Reprinted with permission.

4.2.1 Robot Performance Calibration

As mentioned in Section 2.3.1, mechanical and vision methods exist for calibrating the user frame. One study investigated the accuracy of three calibration methods with the cobot Sawyer from Rethink Robotics [26]. The calibrated user frame was a planar table. The initial method tested utilized a visual calibration process integrated into the cobot. This process involves the use of the cobot's wrist camera and fiducial markers. The method received a repeatability of 1.42 mm and the authors of the study do not recommend using this calibration method for precision tasks. The mean time for the calibration of five different users was 4.3 minutes.

The other two calibration methods in the study by [26] were mechanical. The cobot was moved closely to defined points on the table to compute the user frame. The cobot was equipped with a proximity sensor and the points were markers made in aluminium. The first test used three points and the other one used five points. The three-point calibration achieved a repeatability of 0.33 mm and the five-point calibration achieved 0.12 mm. The mean time for five different users doing the calibration was 5.5 minutes for the three-point and 7.4 minutes for the five-point.

In another performance study, vision systems were used to determine the accuracy of pose estimation for four types of fiducial markers, placed between 75 cm to 200 cm from the camera [37]. The mean error was between 0.093 cm to over 7 cm, but the most commonly observed performance was an error of 0.5 cm to 1.5 cm. The angular error was also investigated by alternating the orientation of the markers. With a 0° angle, the best marker had a mean error of 0.010° but the same marker was also tested with another camera and then the mean error was 2.831°. For 40° the best marker had a mean error of 0.203°. One takeaway from the result is that AprilTag had the best performance for orientation and STag was the best for position when one marker was used. The difference between STag and AprilTag was quite big for the position when one marker was used. The STag was always better in this study with at least 1 cm. Another interesting finding is that the type of camera also affected the result where the lower resolution camera gave a better result, which was also presented in Section 2.3.3.

4.2.2 Vision

Varying kinds of vision systems exist on the market. One type is the robot-specific camera which is built to work with the robots provided by a certain company, an example of this is the Robotiq wrist camera which is compatible with Universal Robots devices such as the UR5e, used in this case. There are multiple examples in the literature of successful case studies where the Robotiq wrist camera has been used in conjunction with different versions of the YOLO algorithm [56], [57]. Another option is to use cameras with more general areas of application, for example, the Intel RealSense camera used in [34].

On top of the division of robot-mounted and external cameras, there are two distinct types of cameras which can be described as 2D, and 3D [58]. 2D cameras are unable to detect depth and only give a flat image. Cameras which are denoted as 3D provide some type of height data (z axis) through stereo vision or with techniques such as laser triangulation, structured light, stereo vision or time of flight [59]. The article by [58] mentions multiple advantages of both 2D and 3D cameras. The main advantages of 2D cameras are their cost-effectiveness, speed and ease of use. Some drawbacks presented are their lack of depth information and sensitivity to environmental changes, such as illumination. The 3D alternatives often come at a steeper price and are more complex to work with but provide benefits including flexibility, depth information and higher precision in object detection [58].

In research by [60], the authors use an In-Sight 5100 camera for detecting the position of a multi-pin connector and identifying the orientation of the grasping. For the project, they used commercial software PatMax by Cognex, which is another example of a company-developed object-locating algorithm. In this case, the camera is used externally instead of being mounted on the robot. Since the aim is to be able to reuse the robot solution for additional stations, a stationary camera like this would not be suitable.

As for the cameras mounted on the robot, there are a large amount to choose from. In Table 4.1 some of the benefits and drawbacks are identified of two types that have been researched during this project. The reason why these two were chosen to be compared was that they both are robot-mounted, which is preferable in this project. Robot mounted will provide flexibility since the cobot can be moved to other stations and applications in the future. They also cover two distinct areas of the robot camera market. One of the cameras is made explicitly for the robot in question (UR5e) while the other is essentially a high-performing camera in the format of a webcam. Important to note is that the presented advantages and disadvantages are observations compiled from the product specifications and observations of each unit.

Table 4.1: Advantages and disadvantages of two cameras researched for use in cobot-vision systems.

Robotiq Wrist Camera	***Intel Realsense D435***
Advantages:	**Advantages:**
Software included for image processing (and other features)	Stereo vision (depth)
Plug and play (relatively easy to use)	Price
Compact	Flexibility (with custom code)
Disadvantages:	**Disadvantages:**
Limited features (expanding requires special skills)	Requires external PC
Universality (only compatible with UR robots)	Not compatible with teachpendant
Price	Complexity to use (coding/connection)

There are several examples of where vision has been used as a tool in combination with a robot or cobot to gain increased quality and/or availability [61], [62], [63]. Because of this, Saab could likely find advantageous ways to use vision in their new production line.

4.2.3 Machine Learning

From the literature study, it was clear that there is a large quantity of object detection algorithms that exist, and they often come in various versions. Some of the most popular applications within robotics seem to be the YOLO or the Single Shot MultiBox Detector algorithm [64]. The authors of [63] used deep reinforcement learning combined with human demonstrations for a robot inserting deformable clips and pegs. Visual- and force feedback controller was trained to solve these insertion tasks. The study demonstrated that the tasks could be solved in under ten minutes of interaction time, without the need for simulation, modelling, alignment behaviours, or reward shaping. The results also showed that the solution was robust to variations in the orientation and position of the sockets. The study was however only made on 3D-printed parts and no real connectors were used. A similar study was conducted by [65] but instead different types of electrical slide-on connectors were used. A large number of tests (13906) were made in various setups with varying levels of difficulty and a success rate of 99.8% was achieved.

Machine learning is often used in combination with vision, especially for object detection [66]. The authors of [67] used a machine-learning object detection algorithm for inserting screws with different sizes. It was trained to see the difference between holes and screws. One used dataset had a high f1-score but there was also a small probability of predicting false-positives. The authors of [68] used deep vision for detecting connector types which can be used for robotised assembly of wire harnesses. In the article 20 types of connectors were used as a dataset and 360 images of the connectors in different positions were used. Two-staged and one-staged detection were used. YOLOv5 was used for the one-stage detection and Faster R-CNN was used for the two-stage detection. The result showed that using deep learning is effective but it can be problematic due to many of the connector types being similar in design. A better performance was achieved by the one-staged detection YOLOv5. The authors suggest further studies for similar exterior design of the connectors by using multi-view image-based and video-based connector detection.

Many of the articles investigated how machine learning can be used in collaboration with humans. The research by [66] showed the potential of using deep learning in human-robot collaboration and how it can take collaboration to new levels. Three Convolutional Neural Networks were integrated to enable assembly. These were used for voice commands, hand-tracking and image classification. The voice recognition system could classify sounds into eleven different classes which were the commands available to the users. The hand-tracking system was used for the interaction between the human and the cobot, especially for delivering and receiving parts. The image classification was used to correctly identify one of the seven types of objects used. The average accuracy for object detection was 99.8% and for voice recognition the average was 94.5%. The hand tracking system achieved an accuracy of 99%. The whole integrated system had an average accuracy of 91.3%, with 511 out of 560 successful tests.

4.2.4 Sensors

During the project, a couple of sensors were studied to establish potential usefulness in the automation of the calibration. Mostly robot-mounted sensors were considered to allow for a more flexible solution. One type explored was distance sensors, particularly photoelectric distance sensors of the diffuse reflective type. They were found to be relatively inexpensive, with the cheaper models sacrificing parameters such as accuracy, repeatability and refresh rate. Ultrasonic sensors were also considered for distance measurements, but they have problems with measuring irregular surfaces and at angles [69].

4.2.5 Error Handling During Insertion Tasks

Research has been made regarding recovery methods when positional errors occur during the insertion of electrical connectors [70]. This specific study used a multipin connector. Spiral search algorithm is a probabilistic technique and the right position may not be detected. The authors state that this method is useful for connectors with a flat edge. The algorithm works as follows: From the colliding point, the connector is moved in a spiral pattern outwards. The correct position is detected with the help of references from the vertical force feedback in the robot. Force feedback means that the robot can measure the forces and torques of its joints to an extent, and use this information for its operations. If the connectors are large enough the spiral search might be a viable option if the connector slightly misses. The smaller contacts such as in Test 2, are however too fragile for this to work as the force is too small for the robot to detect and they are also prone to bending.

4.2.6 Combinations of Technologies

To further envision how a future solution at Saab could look some case studies were studied to find different ways that technologies can be combined into systems that resemble potential solutions to the task at hand.

In the use case presented by [33] the authors present a framework for how they automated SME production with a cobot system. This framework can be seen in Figure 4.2. Here, a couple of the technologies identified in this section, including stereo vision and cobot grippers, are integrated with the control system to provide a flowchart illustrating how a system could be constructed.

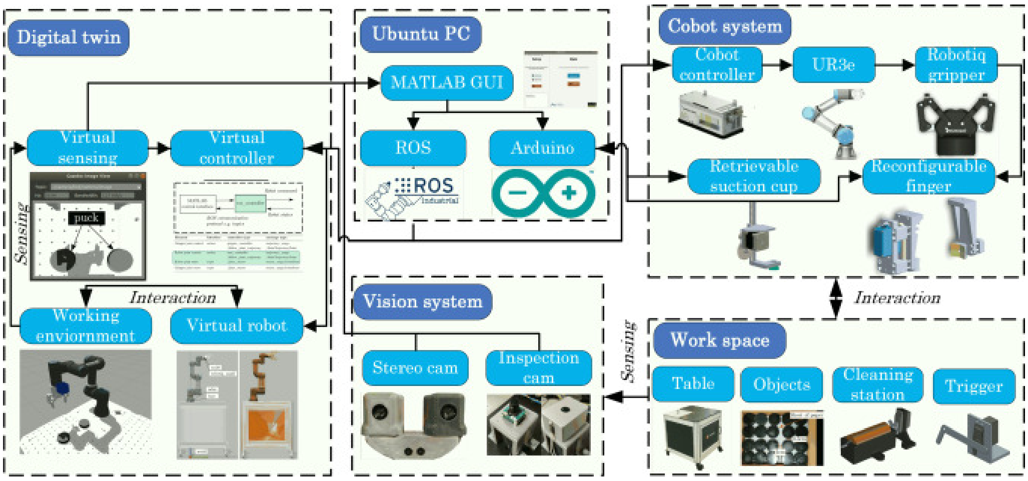

Figure 4.2. Framework for automation using cobot system. [33], CC-BY-4.0

A study by [71] combines a deep vision camera with a convolutional neural network for object detection to insert two types of cables using a robot. The algorithm uses the vision as input to detect the sockets and outputs the type of socket and bounding boxes for the socket position. The centre of the sockets can be calculated with the help of the bounding box. The orientation of the target socket is then estimated. In total, 100 images were used in the dataset and the type of connection and bounding boxes were hand-labelled. Plane fitting, the process of finding a fitting plane (a two-dimensional flat surface) to three-dimensional objects, was used to estimate the roll and pitch angle of the socket and after that, the yaw angle could be estimated. When the position of the socket is obtained, the robot goes to a pre-insertion position. There may be errors in the pose estimation and to cope with these errors Cartesian impedance control is used. This system makes it compliant with positional errors due to the robot's end effector acting like a mass-damper system. The framework of the system is presented in Figure 4.3.

The study by [71] tested the system on two connector types, RJ45 and HDMI, by orienting the sockets differently. The RJ45 achieved a 94% insertion success rate, while the HDMI achieved 77%. Both types had similar position and orientation errors, but the difference in result may be due to the smaller insertion tolerances of the HDMI. The study also showed that changing the roll angle of the connector resulted in a greater impact on the orientation error and the other two angles had little impact. The time to insert the connectors was approximately 8.5 seconds for both types. The authors propose further studies on how the data can be utilized to combine visual and force sensors.

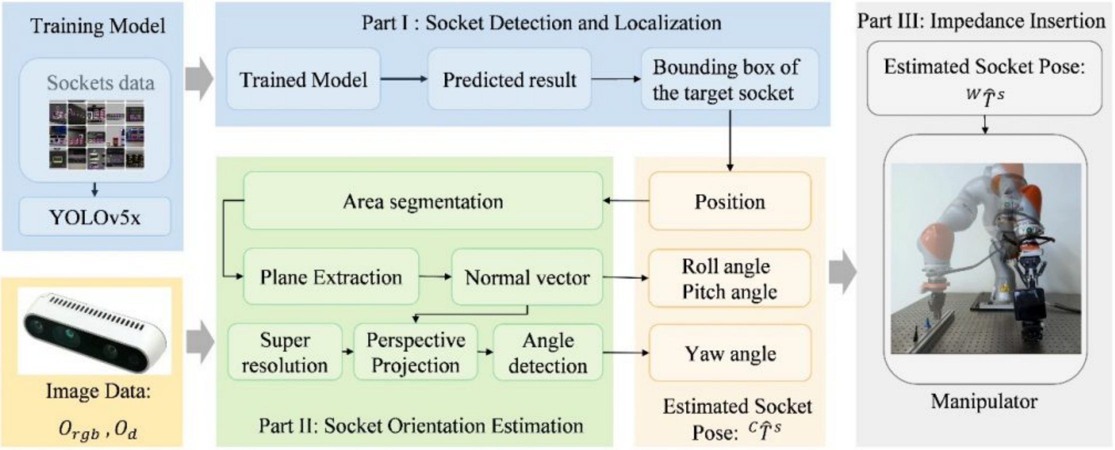

Figure 4.3. Framework for automation using cobot system. [71], © [2023] IEEE.

A popular approach for the building of more advanced systems with integrated technology appears to be the use of Robot Operating System, which was also used in Figure 4.2. Robot Operating System is an open-source library with different software packages and solutions that can be used for robot applications [72]. This could be especially useful as a common ground for combining technology which is not directly compatible. However, security risks have been identified through research [73], [74]. This is worth taking into consideration when deciding on implementation at Saab because of the high safety requirements. There are a myriad of variants with different features such as Rock, OpenRDK, ORCA and TwinCAT. However, if the application itself is simple enough it is also possible to control it through code (python for example), with the catch of missing out on all the benefits of the previously mentioned programs.

4.3 Robot Compliance and CE Marking

When it comes to safety CE marking is a way to prove that your products adhere to the European health, environmental and safety requirements [75]. A CE marking for machines is usually applied for with a complete machine, but cobots are not considered a complete machine because to evaluate if the cobot follows the European directives it is also necessary to consider the application for which the cobot is used [76]. Furthermore, it is mentioned that for an incomplete system, Universal Robots provide a Declaration of Incorporation, which states that the incomplete product complies with the Machinery, Low Voltage and Electromagnetic Compatibility Directives as much as the incomplete machine can. When the completed system is evaluated regarding whether or not the application conforms with these directives, and is approved, only then can the engineer issue a Declaration of Conformity and the cobot application be CE marked. If the integrator wants to further comply with global demands there are more regulations to be followed, depending on what part of the world the robot is to operate in. Some directives that are applicable for CE marking of cobots are for example the Machinery Directive (2006/42/EC) and the Electromagnetic Compatibility (EMC) Directive (2014/30/EU).

4.4 Key Performance Indicators

For this project, the main key performance indicators are availability and quality. According to ISO-22400 availability can be measured using Equation 4.1 [49]. To increase availability multiple approaches can be taken. As shown by [49], by decreasing downtime, transport and waiting time you can increase the actual busy time. This allows for a shorter planned busy time thus increasing availability. The other way to increase availability is to increase production time, which can be done by reducing the setup time [49]. Availability is important for companies because it represents the ratio of allocated production time that is effectively utilised for adding value to products. Low availability indicates that production equipment may be unusable when needed, resulting in customer demands not being met. One example of how to increase availability is to implement automation, as shown by [77]. In the case of this project, the calibration can be seen as a type of setup as it is during a time when there is no testing of the product (which means no throughput). If the results of this project are to decrease the time for calibration this means that availability would increase.

$$Availability = \frac{Production\ Time}{Planned\ Busy\ Time}[\%] \tag{4.1}$$

Quality which is the second parameter looked at in this project can be measured using quality rate, see Equation 4.2 [49]. Keep in mind that the quality rate does not cover all aspects of quality that are taken into consideration during this project. For example, an accepted calibration (which is classed as good) could last shorter than a calibration that is well executed. A well-performed calibration can also give a better accuracy of the test-equipment which can increase the quality in terms of better classifying the right condition of the tested product.

$$Quality\ rate = \frac{Good\ Quantity}{Produced\ Quantity}[\%] \tag{4.2}$$

4.5 Literature Summary

The results of the literature study have been used during the empirical testing of the study to further clarify the need for an automated solution. One example of this is the precision of different robot calibration methods, see Section 4.2.1, which have been compared with the required precision during testing. A majority of the research covered detailed state-of-the-art cases, where one type of technology was researched independently. There was a lack of research regarding state-of-the-art technology combined into complex systems, indicating difficulties in doing so. However, there was no desire to rule out any potential technologies or opportunities using solely the information gained from the literature. Further claims about feasibility are discussed in Chapter 6.

5

Results from Empirical Study

In this chapter, the results of the empirical studies are presented, including current state analysis, the experiments that were done and their implication for automation at Saab. Additionally, this will be concluded and compiled into more condensed suggestions for automation. Concerning the confidentiality of detailed information about the operations at Saab, general terms will be used and sensitive data with connection to Saab will not be presented in the results of this study.

5.1 Organisational Vision and Available Technologies

Before diving deeper into the specifics of the results, it is critical to understand some additional aspects of this project regarding the technology landscape of Saab. This is because this information has had a role in setting the direction for the project and guiding the assessments that have been made.

As described in Section 1.1, Saab is moving towards smarter production which means that some technologies have been invested in already and are available for use. For example, the cobot (UR5e). This means that when the cobot is not used for testing in the new production environment, it is likely that it is free for other tasks such as calibration. Using this technology for calibration operations also means that less potential investment will be needed than opting for another approach (such as another type of robot or system). The work was thereby focused on UR robots, but other robots may be considered if necessary in the future.

Furthermore, to keep a flexible approach for Saab's low volume high variety production there has been a larger focus on automation technologies that can be mounted on, or moved by the cobot between stations. A part of the flexibility is also to find technologies that have application purposes for many of the different steps in production. For example, developing complex product-specific stationary fixtures for automation is undesirable.

5.2 Current State Analysis

The purpose of this section is to give the reader a better image of the current state of the calibration operations at Saab. Understanding the current state is a crucial step in the process of implementing automation. It helps with further evaluation of whether it is worthwhile or even feasible, and to determine requirements for an automated solution. Three calibration processes of different testing stations were observed as part of the CSA. The smart factory initiative of Saab is also briefly mentioned.

5.2.1 Station 1 - CSLM1170023/1

While the type of products tested in Station 1 differs from the ones in the new production line, the calibration process is similar. The procedure was observed two times during the CSA. There are two different levels of calibration, which have to be done at certain intervals. The first operation is performed daily or every other day (Tier-1), while the second one is more advanced and time-consuming and executed less often (Tier-2). A test station overview can be seen in Figure 5.1.

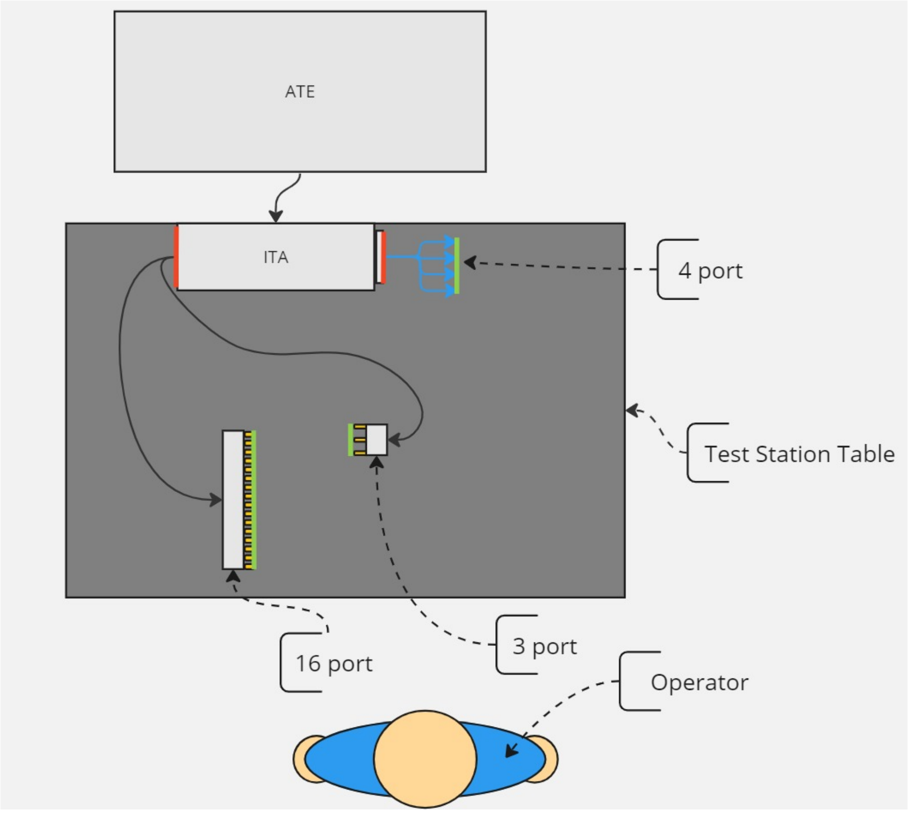

Figure 5.1. Overview of Station 1. Green lines represent the outer interface closest to the unit under test while the red lines show the interface between the ITA and the outer interface.

The Tier-1 calibration works as follows. A power sensor and an electronic calibration module (ECal module) are used for various tests by plugging them into four different ports (4 port in Figure 5.1). Multiple changes are made in the placement of cables. Another operation consists of two cables being connected by an adaptor. The operator tightened the connectors' nuts with two torque wrenches simultaneously, one in each hand. Many of the cables were threaded coaxial cables with a SMA connection, like the ones in Figure 5.2.

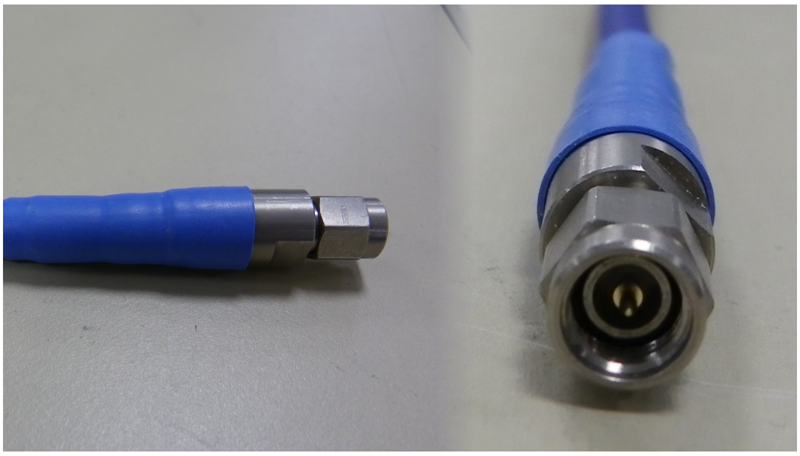

Figure 5.2. Coaxial cables of connector type SMA (male connectors).

For the Tier-2 calibration, the same ECal module is used but it needs to have an adaptor. The test fixture needs to be moved by unscrewing two screws with an Allen key to be able to reach the ports. The ECal module is then docked into the ports of type mini SMP contact and then a test is started. This is done for all of the 16 ports (16 port in Figure 5.1). The adaptor on the ECal module must be inserted as straight as possible. The operator uses a small lifting table to adjust the placement of the ECal module ensuring straight insertion. A ruler was used to position the lifting table parallel to the mini SMP contacts. The time it took to move the ECal module between ports varied between 11-22 seconds. The variation in time was mainly due to the operator sometimes wanting to check the alignment of the ECal module, so the operator looked from many different angles to check. The time for the testing of the ports depended mainly on the software. Around 2.9% of the time was spent on moving and inserting the ECal module, the rest was spent waiting for the test to finish so that the next port could be tested.

The next step in the Tier-2 calibration was to test three other ports of type SMP, which were of another size (3 port in Figure 5.1). Therefore another adaptor was mounted on the ECal module. To test these ports some fixed parts in the station were removed to be able to reach the ports with the ECal module. The lifting table was moved and readjusted for the ports. The ECal module had to be placed on the lifting table differently and was more unstable in this position. This resulted in a longer time needed for aligning the ECal module with the ports. The tests took twice as long as the previous tests but because the manual steps took a longer time, about 10% of the time was spent on manual work. After everything was tested, the operator compared the calibration with reference values to ensure good quality.

One problem that arose during the first observation of the station was that the mini SMP connectors sometimes got stuck on the adaptor of the ECal module when it was unplugged. The operator then needed to use a tool for separating the parts and after that, reinsert the connectors. During the second visit, this problem never occurred.

To attach and remove the cables with an SMA connection, the operator needs to use a torque wrench. However, the nut of the connector must be pre-attached by hand. It is also important to consider that the cables should not be bent or stretched due to the impact on signal quality.

5.2.2 Station 2 - LPEM0300008/1

Station 2 calibrates one of the products which will be tested in the new production line. However, it is important to note that the calibration process for this product may differ from the one in the new production line. The full calibration is done every third month. The process involves several steps on the computer, where the operator must select parameters and settings. Errors by the users can easily occur due to all the repetitive work and little guidance. The manual steps requiring an operator to move and lift objects were few. One common task is connecting a power sensor in different ports. Before connection, an adaptor needs to be mounted on the power sensor. The contacts in the test-equipment can move which allows for some misalignment. Throughout the process cables must be unplugged and the power sensor plugged in instead. For this process, another adaptor is needed. A smaller torque wrench is used to screw the cables with the SMA connector in place.

Another step is to use a calibrating kit containing three smaller devices which test three cases. Each device is plugged in several times in different ports. A small pin needs to be placed inside all these devices. The operator pointed out that the pin has two different connection types, one at each end. The connection types are similar and can easily be incorrectly inserted. If the pin is placed on the wrong side it risks damaging the port. The three smaller devices in the calibrating kit were also similar which can lead to the operator taking the wrong one. Another manual step at the end of the calibration is to place a reference product in the place where the products are tested to check the calibration quality.

Maintenance of the station is required at various intervals. Some tasks need to be performed daily, while others are done during calibration. Examples of actions taken during calibration include removing dust from the connectors with a small vacuum cleaner, cleaning the fixture with a wipe, and checking all cables and connectors.

5.2.3 Station 3 - LPAM1010003/1

In Station 3 the full calibration of the test system is done seldom and takes a few hours longer than the other two stations. For some of the calibration steps, it was preferable to have two operators. One operator holds and connects a cable against a connector (slide-on connection) and the other one starts a test. The distance between the cable and starting the test makes it difficult to do it alone. The cable needs to be inserted as straight as possible and shall not lose contact with the connector to minimise the risk of quality problems, which is why two operators are preferred. This process was the most repetitive of the three stations concerning manual work and mainly consisted of testing all the connector sockets. All these connectors were of similar types and the procedure was repetitive. Because of this, the operator stated that it is cognitively challenging and that mistakes could happen. The operator had some guidance in the computer to see the name of the connector that should be tested next. The names were however quite similar which increases the cognitive load.

A jumper tool was used to connect two ports, which was repeated multiple times. The tools have a set distance which is appropriate for its use. When inserting the tool, the operator had to use both hands to insert both ends at the same time. The station also has some threaded connections which means that the operator must use a torque wrench to tighten these.

5.2.4 Comparison Between the Stations

All stations include the step of disconnecting and connecting cables with threaded connectors. Connectors with screw nuts need first to be tightened by hand and then by a torque wrench. All stations have some slide-on contacts which are calibrated through probing. The contacts are however not the same, the sizes can vary between the stations. Common for all stations is also that the operators need to be careful when most of the connectors are inserted since they must be inserted as straight as possible to achieve a sufficient calibration quality. All three stations have many repetitive manual steps, especially since the same processes are done for many of the connectors in the test station. All tests are initiated through the computer but the amount of settings and time spent in software environments vary between the stations. Generally, the older procedures had more manual steps in the software.

The stations differ in the distribution of manual steps versus computer-based steps. Station 2 involves more computer-based steps and fewer manual steps, such as moving cables and inserting electrical devices into the connectors. Station 3 was the station with the most manual steps and after most of the manual steps, the operator needed to walk to the computer mouse and press START/OKAY. For Station 1, the computer work was more automated and the main task was the movement of devices and cables. This movement was however not as frequent as in Station 3.

The waiting time also differs between the stations. Station 1 had the most waiting time for the operator because of the long time it took to test each connector. During the second visit to Station 1, the operator sometimes left to do other work during the tests because of the long waiting time. Sometimes this resulted in the operator returning late and the calibration process was thereby delayed. For Station 2, the operator worked almost all the time and only waited during some of the tests. Station 3 had some waiting time for some of the tests, but it was much less than Station 1. Station 3 had some paused time however since the operator needed to take a lunch break due to the long required time for calibration.

There was some difference in working procedure between the operators. The steps when the connector needed to be inserted as straight as possible, the level of meticulousness differed. One operator double-checked more if everything seemed right, while one of the others inserted it more on feeling.

From the CSA it was determined that the procedure of Station 1 was a more modern process. This means that future calibration procedures are more likely to have steps that are similar to the ones in Station 1 rather than the ones found in Station 2. The design of Station 3 in the new production line has not been developed fully yet but the current calibration frequency is much lower than the other two stations which is why this one was not chosen over Station 1 as reference. The most important steps in Station 3 are similar to the other stations and can thereby be tested by having Station 1 as a reference. Therefore it was determined to use Station 1 as a reference point for further development of tests and automation solutions, in conjunction with the information gained from the development of the new production line that Saab is implementing.

5.2.5 Smart Factory Initiative

As mentioned briefly in Section 1.1, Saab is moving towards Smarter Manufacturing. While not a lot of information was determined for this initiative yet, there was still importance in investigating it since the potential outcomes of this project will aid robot implementation there. Furthermore, there will be elements from both Industry 4.0 and 5.0 which can provide several benefits for digitisation and production.

A new test fixture with the possibility to test different products will be used in the smart factory. To change a product, setup is needed by changing modular parts in the test fixture. After a product change, calibration is needed since the setup results in a change in the system. The fixture can be seen in Figure 5.3 and the brown part of the fixture is the product-specific module. To test a product, the product is placed in the middle of the test fixture and the lid is closed.

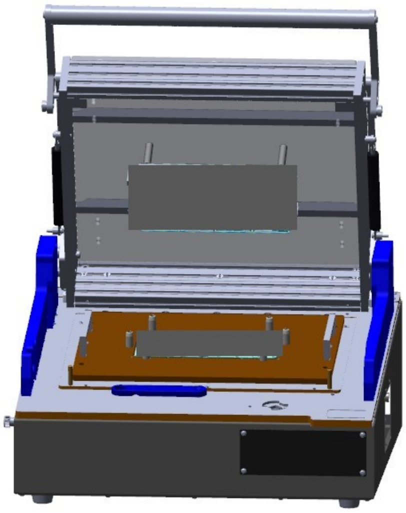

Figure 5.3. The new test fixture where the unit under test is placed.

The products are automatically tested in the new fixture. A cobot will be used for placing products in the fixture instead of an operator. This allows testing to be carried out 24 hours a day, except when calibration or maintenance of the test station is required. An increase in testing frequency and the fact that product changes require calibration will probably result in a shorter calibration interval. This means that if the calibration process can be fully automated, the testing will not be halted if, for example, calibration has to be done during the night when there are no operators present. Through smart development of the test system, the need for an operator to perform the more frequent Tier-1 calibration is anticipated to decrease or be eliminated. This means that an automated solution might only have to be used for the less frequent Tier-2 calibration.

5.2.6 Summary of Qualitative Study

The potential of automating the calibration steps was analysed in the CSA. Some steps were considered to be easier and some more challenging. The similarities between the stations were studied when selecting what can be beneficial to perform tests on and then automate in the production. A specific step for a station can be harder to automate and may not be worth it due to large costs or complexity, such as the one seen in Test 3.

As a starting point for this project, the current calibration process is at a LoA_c 3 and LoA_p 2 on the scale presented in Table B.1. This was determined from observations and information gained during the CSA of the three stations, see Section 5.2.

5.3 Problem Specification

In this section, the problems and challenges identified during the CSA will be presented. The steps identified here will be the foundation for the concept development and also for the test development. This list will be mostly based on Station 1 since it is the most developed of the ones studied and is most likely to resemble the steps of the new production line.

5.3.1 Problems for Manual Steps

- Precision and accuracy are important for calibration contact points and the angular, horizontal and vertical deviations need to be kept low.
- Repetitive and time-consuming for the operator to test all the ports as there is a time delay between each test.
- Complicated threaded connections of the cables that need to be disconnected and reconnected in some of the calibration steps, see Figure 5.2.
- Problems with the snap-on connections as they sometimes get displaced during calibration and have to be re-attached using a special tool.
- Cables should not be bent to avoid affecting the RF signals.
- The ECal modules were not fixed in any way, which could cause them to tip over or have uncertain positions that in theory can affect the calibration quality.
- When connecting cables without the ECal module, they were not fixed in place, causing difficulties for the operator and also uncertain cable positions.
- There were several confirmation checks by the operator for the ID numbers of the kits used to make sure they correlated to the ones in the software, this was time-consuming and could confuse.
- For some steps in the calibration instruction it was advised to clean the stations through vacuuming and cleaning the contacts. This requires fine motor skills and also identifying dust or grime visually which is not a simple task for a robot.

5.3.2 Problems for Digital Steps

- There were no notifications when the calibration steps were finished, so if the operator did other work tasks in the meantime it was hard to know when the steps were finished and when it was possible to proceed.
- Many manual inputs in the software were present, such as input of serial number of the ECal module and selection of steps that should be included for some frequencies which could lead to confusion and mistakes for the operator.

5.3.3 Identified Challenges for Automation

This section presents some of the challenging areas that were identified during the CSA which could prove problematic for automation and that are extra important to think about when automating this process.

One identified challenge is to connect the cables with the SMA connector, see Figure 5.2. The threaded connection of the cable needs to be tightened with the right torque, otherwise, there is a risk of losing accuracy in the calibration if the torque is too low. However, if the torque is too high, the equipment could be damaged due to for example stripped threads. The threaded connections might also pose a challenge for the robot or any eventual automated solution as near-perfect alignment is required and thread matching could be difficult. Another challenge in the calibration process is that some of the manual steps require handling up to three objects simultaneously. This needs to be considered during tool, fixture and automation sequence design because the robot for this case study can only use one end effector simultaneously. The calibration process step of inserting connectors also requires high precision and accuracy. Choosing the correct coordinate systems and localization methods for robots in the system can be challenging when handling demanding tasks.

There are also challenges connected to the calibration area. Some of the calibration steps were performed in tight areas and reach could become a problem if tools are not designed properly. Furthermore, the automation equipment must be appropriate for use in an ESD environment and include no magnetic components to ensure that it does not disturb the calibration quality. If an automated solution has the robot moving around, using pneumatic solutions could be problematic as it requires a compressed air supply, which is commonly a fixed installation.

5.4 Test Results

In this section, the results of the performed tests will be presented alongside with the decisions made throughout the testing procedure.

5.4.1 Test 1 - Insertion of Coaxial Cable with Adaptor

This test slightly resembles the types of connectors observed during the calibration at Station 3. The gripper extension for Test 1 was designed by importing the drawing of the coaxial RF cable end to CATIA V5 and tracing the shape in a 1:1 scale gripper. The gripping point for the tool was designed with an optimal distance for the pneumatic gripper used, as specified in the data sheets from the manufacturer. The design features chamfers and fillets which act as guides both when the gripper is aligned around the cable and when the gripper then closes. The gripper was also designed in a way so that when the gripper closed, the gripper was offset 2 mm inwards on each side. The reason for this is to make sure that the pneumatic gripper (Schunk) is not at the end position of its stroke. The offset makes sure that the gripper hits the cable 2 mm before the end position, making it efficiently maintain clamping force. The inner walls of the gripper near the gripping point, are also offset outwards to ensure that contact is not made between them as the gripper is closed which could result in a loss of clamping force for the grip on the cable. See

Figure 5.4 for an image of one side of the gripper.

The gripper performed well for this test but there were a couple of factors that need to be addressed. One factor is the size, this gripper obstructed the two nearest ports from the one in which the cable was situated. Another factor is the friction force between the cable and the gripper which has to be greater than the force required for pulling the cable out from the socket if the gripper has this type of design.

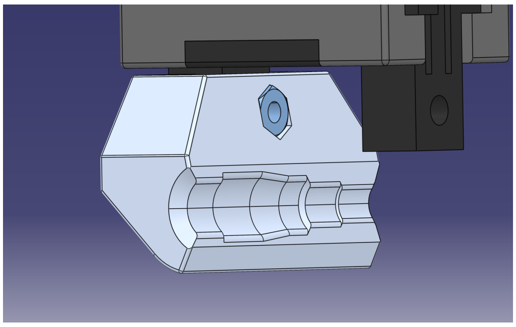

Figure 5.4. CAD model of gripper design used for Test 1 and Test 4 with traced profile of coaxial RF cable mounted on the Schunk P50 pneumatic gripper.

Figure 5.5. Gripper holding coaxial RF cable.

For Test 1 without variations the cable was inserted correctly in all 75 cycles, or 150 contacting attempts. With angular variation at ± 40° from the horizontal plane all 50 cycles were successful. This means that there was a total of 125 cycles for Test 1 and 250 contacting attempts. The total success rate for this test was *250/250 = 100%.*

Keeping the other end of the cable loose resulted in almost no changes in gripping position. The reason for this depends mainly on that the socket held the cable straight and the cable was stiff where the gripping took place. This resulted in no cable bending and consequently no bigger variations in cable placement in the socket.

The socket however required some force to insert the cable and it was important to make sure that the robot was programmed to fully insert the connector without damaging the socket or connector. During the programming of Test 1, it was noted that there was a significant risk of not pushing the cable far enough for a proper insertion. This resulted in the cable not being plugged in all the way, and after each cycle, the deviations became bigger and bigger as the errors were added for each continuous cycle. For the real test, this was never a problem because the robot was programmed to insert the cable until the movement was restricted by the test rig, which made sure that the cable was properly inserted. When doing so, there could be a risk of damaging the components.

5.4.2 Test 2 - Insertion of QuadraPaddle Contact

The gripper for Test 2 was designed to allow gripping the cable from either the side or from the rear. Figure 5.6 shows the design that makes it possible to grab the cable from two sides. When gripped from the side (robot arm perpendicular to the cable), it can be grasped from all angles around the cable. When gripped from behind (parallel to the cable), the gripper can also grasp it from all angles. The reason for including grasping options is due to the limited space between the connector sockets of this type of connector. The gripper for this test needs approximately a 7x2 grid clearance around and including the gripped connector. The types of cables used for this test are lightweight, which makes them a bit unpredictable in their behaviour. This needs to be considered so that the cables are not tangled or ripped by the robot. Worth to notice is that this is not an RF cable, but a DC cable. Therefore avoiding bending in the cable is not of the same importance here as for the other tests.

The gripper was designed based on the profile of the cable at the location where it was supposed to be picked up. The profile was offset inwards to ensure good contact between the cable and the gripper. Figure 5.7 shows the used 3D-printed gripper for Test 2.

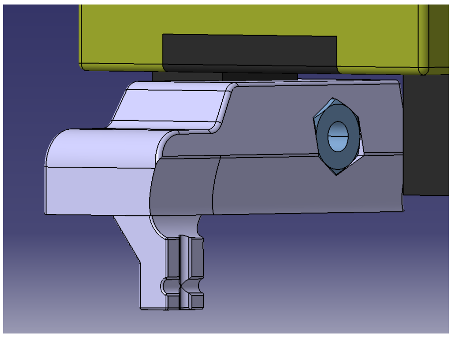

Figure 5.6. CAD model of gripper design used for Test 2 mounted on the Schunk P50 pneumatic gripper.

Figure 5.7. Gripper holding the cable in Test 2.

All the 60 cycles of connector insertion were inserted correctly. The required force to insert the connector was low and the socket made the cable stable meaning that the connector was not hanging downwards. The variation in the test made no impact on the result. It was still possible to grip the connector all the time correctly without the cable sliding inside the gripper with a lower pneumatic pressure. The total success rate for this test was *120/120 = 100%*.

5.4.3 Test 3 - Coaxial Threading

For Test 3 a couple of ideas were evaluated. In Figure 5.9 the most promising idea is presented. The presented idea, see Figure 5.9, was the concept after a couple of iterations. Some examples of changes during development were discarding rubber belts due to a lack of friction and the setup of the three rotating points had been iterated to have a good fit. Multiple other concepts have also been sketched but discarded due to reasons such as complexity or feasibility. One idea was to take inspiration from the type of torque wrench currently used in production. This design was hard to replicate in a gripper as this type of tool had to be aligned with the nut multiple times due to the number of turns required for tightening the connection. Otherwise, the cable would have obstructed the motion of the robot. The initial turns were also problematic. A limited amount of space only allowed the nut to turn less than one full rotation when trying to properly align the threads, which did not prove sufficient for making the cable stay on the connector when re-aligning the tool for the next turn.

The presented concept idea in Figure 5.8 and Figure 5.9 was that one of the three wheels on which a belt was placed could be motorised, and used for spinning the nut at the end of the coaxial cable. The idea was then to integrate this solution with a gripper to allow for picking up the cable and rotating the nut while holding the cable. Initially, the attempt was made without the cog-like attachment seen in Figure 5.8, but the friction between the belt and the nut was not high enough and the torque required was too large for spinning the nut. However when the attachment seen in Figure 5.8 was added the rotation was much easier for the tool to perform. At this stage of development, one major issue was identified with the connection. Minor changes in the angle of the connector, forces orthogonal to the cable and misaligned threads all contributed to fluctuating friction in the connection and the nut easily became stuck. This posed a major challenge for any solution intended to solve the task. With the observed variances in prior testing equipment and the difficult behaviour of this prototype, it was determined that it was not worthwhile, as the development of a solution was approximated to require resources which were not available. Therefore, the focus was shifted to the remaining tests.

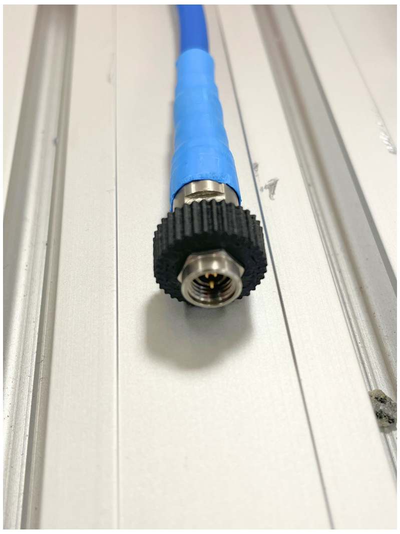

Figure 5.8. Teethed adaptor attached to the nut of the coaxial cable for increased leverage and friction.

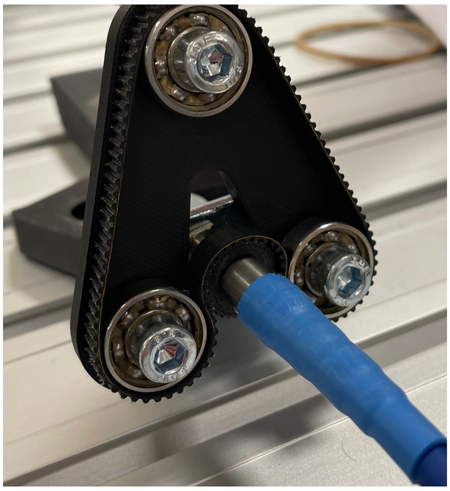

Figure 5.9. Concept evaluation of using a belt for rotating the threaded part of the cable.

5.4.4 Test 4 - Coaxial Slide-On

The same gripper as for Test 1 was used for this test, see Figure 5.5. The test was run for a total of 50 cycles, resulting in 140 contacting attempts, due to ten failed cycles subtracting on average one attempt each. For the first 25 cycles, having the other end of the cable fixed in the same position resulted in a success rate of 100%. The next 25 cycles introduced variations by leaving the other end of the cable free. Different positions were evaluated in between the cycles. When variations were introduced, 15 out of 25 cycles were successfully performed. The amount of contacting attempts before failure for the ten failed cycles was included. Sometimes the robot failed on the first attempt during the cycle and other times on the second, resulting in the remaining attempts of the cycle being excluded. This gave a success rate of *55/65* for the contacting with variation. The total success rate for this test was *130/140 = 92.9%*

Some of the varied positions resulted in angular deviations of the cable position which caused the gripper to grip the cable incorrectly. When the cable was gripped in the wrong position it caused the robot to misalign the cable with the socket. In some of the cycles, it was gripped slightly wrong but due to the chamfered edge in the design of the gripper, it managed to slide to the right position. It was also noted that during some of the insertions, the connection seemed to experience some friction due to slight misalignment.

5.4.5 Test 5 - Spring-Loaded Coaxial Probe

This test used a spring-loaded coaxial probe connector which was relatively small. The connector can be seen in Figure 5.10. This connector is spring-loaded in two steps. The first smallest part, to the right in Figure 5.10, contacts the inside pin of the adaptor in Figure 5.11 and can be pushed down until not visible from the side (maximum travel 1.7 mm). Once this happens a larger spring starts to compress if further force is applied (maximum travel 5 mm). The small probe was compressed fully during testing and the larger spring was only slightly compressed ($\approx$ 0.5 mm). The small probe used for contacting has an outer diameter of 0.9 mm. For this test an adaptor was attached to the coaxial cable used for previous tests and the large gripper used for Test 1, see Figure 5.4.

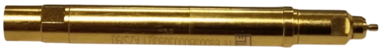

Figure 5.10. Spring loaded coaxial probe used for Test 5.

Figure 5.11. Adaptor used for contacting in Test 5. The threaded end is connected to a coaxial cable in this test.

A fixture with a design resembling the actual fixture to be used in production was modelled. To save material and time, only one-fourth (one corner) of the real fixture was modelled and 3D printed. Since the type of connector will be the same across the entire fixture it was determined sufficient use only a part of the real product. The modelled fixture can be seen in Figure 5.12. Two of the fixture holes were modelled as chamfered, this is not how the real product is designed but it was determined interesting to evaluate whether or not this type of design could be beneficial for the robot if slight inaccuracies were present. These types of guides are designed to account for small errors in accuracy which usually are present when working with industrial robots. Other than this change the design was representative of the real fixture. The way that the connectors were placed in the holes can be seen in Figure 3.12. For the design of the fixture, two counter-bored plateaus were included to seat the connector properly. This was not present in the model obtained by Saab but was deemed necessary since without it the connector would have fallen out. However, when working with fixtures made of metal the probe is manufactured to be press fit. A widened outer diameter was also created at the top of the holes to make sure that the inserted male contact (adaptor) could properly engage the spring-loaded pin of the female seated connector.

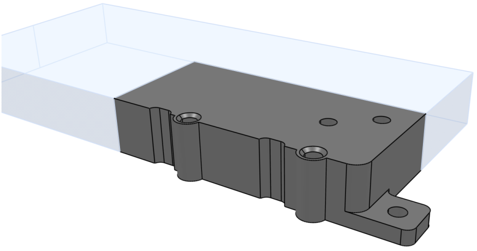

Figure 5.12. CAD model of fixture used for Test 5.

For the 40 cycles run in the non-chamfered holes, 39 out of 40 cycles succeeded. This means that 79 out of 80 contacting attempts were successful (≈ 99.8% success rate for contacting). The attempt failed because the robot hit the edge of the hole, triggering the emergency stop. Since there are eight contacts across the whole test board in the real setup, this means that nine out of ten calibrations would be successful. In this case, it is a success rate of 90% for the whole calibration procedure assuming that each port is contacted once. The time it took for the robot to go from one contact to the other was 8 seconds.

As for the 40 cycles performed with chamfered holes 77 out of 80 contacting attempts were successful (≈ 96.3% success rate for contacting). All of the failures happened for the same hole of the two tested. The unsuccessful attempts failed because the SMP male missed contacting the female connector spring. The robot misaligned with the hole and the chamfer corrected the error too late (the SMP pin passed the tip of the spring-loaded coaxial probe before the misalignment was corrected). This type of misalignment failure is illustrated in Figure C.3 where it can be seen that as the side of the adaptor hits the guiding edge, the pin is already past the socket. If each of these fails were to happen for different calibrations this would give a success rate of 70% for whole calibration procedures. The time it took for the robot to go from one contact to the other was 20 seconds. There was a larger distance between the contacts and the accessibility was worse when reaching this point compared to the first 40 cycles. It is important to note that a lower speed of the robot was selected in case something went wrong.

For the angular variation test, 40 out of 40 cycles were inserted correctly when the fixture was rotated 140°. For the 180° rotation of the fixture, the result was that all 40 cycles succeeded. This means that the angular variation test adds a total of 160 successful contacting attempts. The tests that were performed planar to the ground (chamfered and non-chamfered) had a total of 156/160 successful contacting attempts. The total success rate for Test 5 was *316/320 = 98.8%.*

After the testing, a quality problem was discovered with one of the spring-loaded probes. The small pin used for contacting was slightly bent. The damage probably came from one of the failed attempts when the probe missed the cone since all the failures happened for the same probe.

5.4.6 Additional Tests

For the test using RoboDK as a third-party program to introduce reference frames, the measured points were successfully imported into the software and a coordinate system was defined that resembled the real production environment. Due to licensing limitations of the software, it was not possible to export the robot program back from the software into the real station which hindered the action of verifying the accuracy when using reference frames instead of programming the robot manually.

5.5 Evaluation of Test Equipment

This section serves as an evaluation of the equipment used during empirical testing and how it might have affected the results.

5.5.1 Robot Performance - UR3

The robot used for testing was the UR3 which performed well but had some problems with its servos which made the robot jittery at certain speeds and angles. There is a possibility that this could have impacted the test results. The behaviour is determined to have a slight negative impact on the testing as the robot becomes less accurate in its movements. However, the instability was mostly seen during certain movements. Typically rapid motions or movement near the joint limits. Therefore the robot was programmed in a way that avoided most of the impact this had. Furthermore the use of wait commands before insertions seemed to reduce the jitter additionally. With all of these precautions, the impact of the robot's behaviour on the test results was deemed to not have any significant impact on the test results.

The robot in itself has a repeatability of ±0.1 mm while the UR5e has a repeatability of ±0.03 mm [78]. The size of the robot was not an issue during testing but the UR5e is bigger than the UR3 which could be negative for certain applications. During the testing, it was never identified that a larger robot arm with an approximate size of the UR5e would hinder its success in performing the tasks. The main factor identified for reachability and access was the design of the grippers.

5.5.2 Grippers

A pneumatic gripper was used for all tests due to it being available for use, but an electric gripper was also tested for grabbing the cables and it was determined that it could sufficiently do so.

The gripper used for Test 1 performed well, but there were a couple of design improvements identified. Sometimes when the cable was not gripped correctly the chamfered guides were not large enough for the cable to slide into the correct gripping position. Another issue with the design was that the gripper did not lock two out of six degrees of freedom, where one of them was translation. This means that the gripper entirely relied on friction for pulling the cable out. Finally, some wear could be seen on the cable from the gripper which is a combined result of the gripping force, gripper material, gripper design and robot programming.

The gripper used for Test 2 performed quite well as it did not experience nearly the same forces as the one used for Test 1. This gripper also was able to perform its task using much less force as the connectors were smaller and experienced less friction during insertion. Another key takeaway from this test is that stoke length and gripper size heavily influenced the amount of obstructed space around the cable that was gripped.

6

Discussion

This chapter will discuss the results of the project, provide suggestions to Saab and answer the project's research questions.

6.1 Calibration Operations at Saab

As discussed by [79], traditional manufacturing systems and industrial robots (excluding cobots) are not flexible enough to handle the variation in both customer demands and product changes. Furthermore, it is mentioned that implementing cognitive abilities in automated systems is a necessary step to allow for human-robot collaboration and more efficient changeovers. This in turn could be useful to manage these variations. From the CSA, see Section 5.2, it has been identified that the calibration operations at Saab contain many different elements that are quite challenging from an automation perspective. Some examples seen during the CSA are the threaded coaxial connectors and the small contacting probes, see Figure 5.2 and Figure 5.10. These challenges mainly come from the fact that Saab produces complex products, needing multiple manual steps with fine motor skills required for completion. The intricate steps both inherited from the nature of the products that are tested but also from the fact that the production overall is mostly manually performed. Multiple tests were made to solve or determine how feasible automation of the different calibration steps is. Another important factor for Saab is the longevity of implemented solutions. Usually, equipment is kept approximately for more than 30 years, which puts requirements on implemented equipment to have the possibility of being maintained, kept up to date and operable for the entirety of its lifespan.

Smart Factory Initiative

Saab is currently developing a smart production line, as briefly presented in Section 5.2.5. This comes with many potential benefits.

Calibrations today are done at the outer interface. Some of the connectors tested in this project are present at the interface represented by the red lines. It is possible that calibration data could be split at the red interface to allow for storing the calibration data between the ATE and ITA, while a change of products happens for example. This can potentially allow for time savings as only the path between the red and green interfaces has to be checked after a fixture change.

For the mechanical aspect of the new station, some design elements aid an automated solution. First off, the simplification and standardisation of fixtures to support multiple product types is very beneficial for automation, which is something that can be seen in the new fixture. This enables for example reusable programming and robot tools, along with making the implementation of product changes smoother. Additionally, the new fixture is more robot friendly as it utilises levers and handles for closing and opening instead of solutions like screws or clasps, which require human dexterity. It is worth evading steps that require human dexterity when further developing the solution. The main aspects found important for automation regarding new fixture design and subsequently, product design are presented in the following list.

Design aspects for fixtures

- Use guides whenever tight tolerances could become a problem. During for example insertion tasks or alignment of components.
- Investigate degrees of freedom to avoid over or under-constraining fixtures or products.
- Do not use components with loose parts, such as clasps. The behaviour of these is hard to account for when automating.
- Leave room in fixtures for integrating sensors to allow for collecting live information during automation tasks.
- Have accessibility in mind when designing fixtures. A robot, with an end effector, takes up more space than anticipated.
- Use rigid and durable materials and mountings for the fixtures. A potential error from an operator or forces from the robot should not dislodge the fixture from its position and require re-calibration of user frames.
- When working towards more standardised testing procedures, modularity could be an aspect to consider in fixture design. This might make it possible to change small parts of the fixture instead of using an entirely different fixture.

Design aspects for the products

- Use connector types that the robot is capable of handling, to the extent possible.
- Investigate design additions to facilitate not over or under-constraining the unit under test and avoid potential buckling, damage or accuracy deviations. For example, the 3-2-1 locating principle.
- Design products that have options for handling, such as flat surfaces for a vacuum gripper or accessible gripping points when using a finger gripper. Avoid placing fragile components in these locations to mitigate the risk of damage.

As seen during the CSA, there are large deviations between operators and stations which are hard to capture using traditional measurements and data collection. Introducing digitalized solutions offers multiple benefits. It enables the collection of high-quality and precise data, that could be analysed with for example artificial intelligence. Through finding deviations or patterns there is an enhanced foundation and possibility for continuous improvement work within the organisation. Some examples of data that could be collected are data regarding quality rate, cycle times, downtime and throughput. Another possibility is to count the amount of contacting attempts for a connector, which could be beneficial to determine when replacement is necessary. The data could also aid in production planning and decision-making. If the control system knows that no orders or products will be processed in the next hour, and calibration is due in a couple of hours it could re-plan and do the calibration immediately.

The interconnectivity of a smart solution could also open up possibilities for remote control and initiation. If the production stops during the evening due to an error, an on-call operator could connect remotely to assess and hopefully resolve the situation so that production can continue. This is with the presumption that all necessary safety regulations allow for this type of operation. Lead times for process initiations and confirmations can also hopefully be reduced through quick communication within the system.

6.2 Insights from Test Results

This section will discuss the results of the tests and their implications. There is an important aspect that impacts all of the tests. The UR3 robot used for testing lacks the ability to create reference coordinate frames, which is otherwise a useful tool for robot programming. Since the programs for all of the tests are created without reference coordinate systems, it means that the repeatability of the robot is utilised here. This needs to be taken into consideration when evaluating the tests and is also important to consider later on during the implementation of a solution. The cobot UR5e, which Saab will use for product testing, has the ability to be programmed with the use of reference systems.

6.2.1 Test 1 - Insertion of Coaxial Cable with Adaptor

One important finding in Test 1 was that this type of socket requires a significant amount of force to be inserted correctly. This sets requirements for the gripper, as there should be no risk of slipping between the connector and the gripper. Before the development of custom grippers for testing, an attempt was made to insert the same connector with a gripper that was not specifically designed for the cable type. This resulted in the cable not being inserted fully because the gripper slipped before the connector was inserted. The inside of the gripper in Test 1 is designed in a cone-like shape that works well for one of the directions. When the gripper moves in the direction where the cone is narrower, there could be a risk of slipping if the friction is not large enough between the gripper and the cable. This may be due to several factors, including the choice of material, environmental conditions, wear and tear, or the grip force applied. Therefore it is advisable to design the gripper with a small edge in the front that latches on to the last part of the cable before the nut, this was not done during testing as it was thought that the friction would be enough. As discussed in Section 5.4.1 the gripper obstructs the two nearest ports when gripping the cable. This could be mitigated by a slimmer gripper profile and limiting the stroke of the gripper.

6.2.2 Test 2 - Insertion of QuadraPaddle Contact

The second test proves that the smaller cables can be inserted by the robot, as long as there is enough precision in the robot program. As for the gripper, it obstructs some ports around the cable it is grabbing. This could be reduced by using more rigid gripper materials and limiting the stroke of the gripper, reducing the need for a bulky gripper that requires as much space when opening. Changing the gripping point further back may reduce the obstruction to other sockets but this was never tested. The reason for this is that the gripping point will be in a more deformable and have a longer distance to the contacting tip, which increases the complexity of the task and the ability to solve it, as mentioned in Section 5.5.2.

Just like in Test 1, the gripper must have a good hold on the connector. A risk of switching from the 3D printed gripper to an industrial one made of for example metal the potential reduction of the friction, causing sliding. It is probably advisable to have some type of other material with higher friction, such as an elastomer, or a textured surface to maintain the grip of the cable without needing excessive pressure from the gripper.

6.2.3 Test 3 - Coaxial Threading

Test 3 quickly demonstrated that the potential benefits of success were outweighed by both increasing complexity, but also a significant risk of failed operations which could lead to large costs. The absence of similar solutions for the threaded connectors during research in both academic and industrial cases led to the anticipation of this result, though with some doubt. It is important to note that this test does not prove that the task is impossible, but with the obtained results, it is suggested to approach the calibration operation with other means. Bayonet Neill–Concelman (BNC), which is another connector type, has been seen successfully attached by cobot. Substituting the SMA connector for a BNC type, or for the slide-on type tested in Test 4 (see section 5.4.4, could be an approach to consider in the future for the cases where it is possible to change connection type given that the performance of the product is not affected. It could however be very time consuming or not worthwhile to change the contact type for current products. The threaded connectors are of importance for Saab because of their signal quality. However, it is the construction of the current products that affect the design of the test-equipment. One potential solution to the problem of the threaded connectors is to redesign the process in a way that eliminates the need for them to be unplugged and inserted. Most of the threaded connectors were present in tasks related to connections to the ECal module. This suggests that, for example, using multiple ECal modules could potentially reduce the need to insert the connector for some of the tasks. If a change is not possible, an operator will be needed for this specific task. The takeaway is that it can be valuable for an automated calibration to have another type of connector if possible. It would eliminate the need for manipulating the nut on the SMA connector and would require less advanced grippers. A BNC connector would also avoid the hassle of ensuring the correct torque as there is only one pre-set position for when it is connected.

Another insight from testing with the UR3 robot is that it could be beneficial for the calibration to have a dual-armed robot instead of a single-armed robot. For processes where it is necessary to perform two steps simultaneously, a dual-armed robot offers a greater range of possibilities for solving these tasks and can reduce the complexities involved. For Test 3, this may eliminate the need for an advanced gripper since one arm can hold the cable in place and the other one can enter the nut.

6.2.4 Test 4 - Coaxial Slide-On

The most interesting discovery from Test 4 is the importance of having a gripper that can handle angular variations of the cable when high precision is needed and the robot is programmed to approach decided points. Ten out of 25 cycles failed because the gripper was unable to grip the cable correctly when the position deviated too much. The gripper was able to correct some of the smaller deviations due to the chamfered edges, resulting in a successful cycle. The design of the gripper limited the use of chamfer and if larger chamfer radii had been used it may have been possible for the gripper to succeed with some of the failed cycles. However, it may not be possible for another gripper design to solve all types of angular deviations and alternative solutions need to be explored. It is important to note that some of the tested scenarios may not be applicable at Saab as bending cables should be avoided and the cables might be in a fixed position. There may always be some deviations in the position because cables are flexible, therefore it was relevant to test as many variations as possible. Without variation, the test achieved a success rate of 100%. This shows the importance of having a controlled environment that is the same every time, for example by having proper fixturing of equipment.

Another interesting finding was how the slide-on contact seemed to experience increased friction for smaller misalignments. The other sockets in Test 1 and Test 2 have better edges for steering the connector right if this occurs compared to the socket in Test 4. Additionally, there is a difference in the slide-on contact as the contact goes over the socket. In the other tests, the robot always put the connector inside the socket. The surface of the connector is also threaded and therefore the friction seems to increase.

6.2.5 Test 5 - Spring-Loaded Coaxial Probe

As presented in Section 5.4.5 the idea of adding the chamfer was to aid the robot in hitting its target because of the accuracy needed for the type of contact, see Figure C.2. Upon testing, the result was found to be worse than for the non-guiding holes seen in Figure C.1. As discussed in [31] and also presented in Section 2.3.2 there are multiple locating principles for fixture design, with one of them being V-guides. There was a problem which arose for the chamfered hole where the pin of the male connector was guided too late, see Figure C.3. To mitigate this, a protruded chamfer like the one illustrated in Figure C.4 would be necessary as it guides the connector before contact is made. Unfortunately, this type of raised surface could be difficult to implement in the specific case at Saab because contact needs to be maintained from the circuit board to both the surface of the fixture for thermal reasons and to the connector pin, which would be difficult. Another solution could be to add guiding pins to the male contact, and design chamfered holes in the cooling plate as guides instead to ensure proper alignment before contact, see Figure C.5 and Figure C.6 for concept illustrations.

For the test using the chamfered holes, the robot failed at the same hole all three times. This could be because of an error in positioning that was unintentionally created during the programming of the robot. The chamfer shows a great ability to redirect this small error for the male connector to still be inserted in the hole which is a valuable lesson even though the connection failed as previously mentioned. This also reflects the importance of guides when using reference systems instead of online programming through the teach pendant. The small error that was present here corresponds to errors that could be seen due to movements in fixtures, equipment and programming in the real application. The non-chamfered holes worked well for this test with online programming but from the testing, it is safe to assume that the errors that will be present for the real station could prove a challenge if no guides are used.

6.2.6 General Takeaways from Testing

There were a couple of aspects noticed during testing that are relevant to keep in mind when implementing an automation solution. Multiple sensitive process steps could go wrong during testing, for example, the connector could miss the socket and the gripper might not grip the cable correctly. One way of handling this is the force feedback discussed in Section 4.2.5. The force feedback might be difficult to use for smaller connections where the force is not large enough to detect, such as the ones in Test 2.

Another important takeaway is that small changes in the position of either fixtures, robot, gripper or products can impact the success rate significantly. If something changes in the station such as the position of the robot or the position of the interface that is used for contacting it could lead to the whole robot program using a misaligned coordinate system, which could make the very precise operations hard to perform. Therefore, a way to quickly account for changes like these needs to be implemented. To correctly calibrate the position of the robot or the reference frames a distance sensor with high accuracy could be used to re-measure work objects automatically, as discussed in Section 4.2.4. Opting for a highly accurate sensor for precision is recommended, as it could be used to obtain points which then are used to calibrate the reference planes used in the robot programming. A general approach for this is to measure six points with the laser distance sensor to align the reference frame that is used. Usually, the frames are placed strategically to be close to each of the working areas in which the robot is performing its tasks. This should be fairly fast and only take a couple of seconds per point, as the robot can move quickly and the response times for laser sensors are easily sub one second. This seems to be a fairly inexpensive solution compared to using vision for this task as no machine learning model has to be developed. However, if larger deviations occur this method would require a manual re-calibration as the robot might not find the correct surfaces to calibrate against.

As briefly discussed in Section 6.2.5 errors affect the performance of the robot solution. In the real application, the presence of errors is unavoidable due to a multitude of factors. For smaller errors guiding features could be enough but when these errors become large enough the system will eventually fail. Just like for the test systems at Saab, this deviation could be handled through calibration. This calibration could be both for the reference frames used for the robot program and the tools that are used (their TCP). Since a flexible solution is desired these frames need to be easy to calibrate both for operators and technicians. The reference frames could be calibrated manually by using a probe to measure points for aligning the frame. Another alternative is using a laser sensor to measure these points automatically like the ones presented in Section 4.2.4, as discussed previously in this section. This is to ensure that the results of the real solution do not differ drastically from the test results, as the test results essentially are a perfect case scenario since each contact is aligned manually.

6.2.7 Sources of Scientific Error

It is important to consider how the designed tests, which are performed in a controlled environment, differ from the actual solution, as there is a possibility of procedural errors in the testing process. As discussed in Section 6.2 the programming of the conducted tests is done using the teach pendant of the robot system (manually programmed). Therefore it is uncertain how the process will react to variations when using reference frames for positioning instead. The tests have all been induced with varying disturbances, which serve to replicate both the real production environment and the variations that could occur through programming with reference frames. However, it is uncertain if these variations are of the same magnitude or characteristic as those that will be present in the real station, despite the careful selection of variations. Therefore the use of guides and smart fixtures has been advised, not only as it is common practice but also to account for errors that have not been present during testing.

There is also the possibility of human error. A negative test result could have been interpreted as positive if for example a connector was inserted, but the person performing the test did not notice that it was not fully inserted. To minimise this, there were always two people observing the tests, which would reduce the likelihood of the result being misinterpreted.

It is also important to avoid bias, such as observer bias towards the goals of the research [80]. Just like the authors suggest multiple observers have been used during the testing along with standardised criteria whether or not the test is a fail or a pass to minimise the risk of observer bias. This would be further improved if multiple independent observers were present during the tests. Another type of bias is design bias, which relates to the way that the study is designed [81]. To mitigate this bias, the test design was communicated as transparently as possible to allow for proper peer review, along with continuous feedback from supervisors regarding the testing. It is important to recognise that these measures do not fully guarantee bias-free research, as it is difficult to avoid bias completely. The actions have rather been taken to reduce the impact of the bias on the research made.

Finally, it is essential to discuss the generalisability of the results [82]. Although the results derived from this project may be of interest to other industrial applications, it is important to consider that the suggestions and conclusions drawn are based on a specific industrial case. Therefore, it is not appropriate to assume that the results will be the same for other similar industrial cases.

6.3 Connecting Test Insights with the Calibration Process

For the tests to yield any valuable information it is important to consider how they relate both to the performance and the design of the calibration process.

6.3.1 Expected Impact on Process Performance

In this section, the test results will be connected to both availability and quality which are the main KPIs and performance parameters considered in this project, see Research Question 1. A summary of the potential impact of each test is given in Table 6.1, while more details are given in the rest of Section 6.3.

Table 6.1: Overview of KPI impact of automation for individual tests, only connected to the specific process step. Range values meaning (-3) very negative, (-2) negative, (-1) slightly negative, (0) neutral, (1) slightly positive, (2) positive and very positive (3).

	Test 1	Test 2	Test 3	Test 4	Test 5
Availability	**(1)** Slightly faster cycle times.	**(1)** Reduced time for locating correct slot.	**(-3)** Many problems, not feasible yet.	**(-2)** Low success rate.	**(1)** Faster alignment.
Quality	**(0)** No significant difference.	**(0)** No significant difference.	**(-3)** Many problems, not feasible yet.	**(-2)** Misaligning causes major wear.	**(3)** Consistent insertion distance and angle .

Quality

The test results gave some indications of how an automated solution will affect the calibration process. In terms of the quality of the calibration, the result shows in general that a robot can improve the quality. The tests showed that the robot is capable of inserting the tested connectors straight and with high repeatability. This means that all connector matings in calibrations will be done similarly. From the CSA it could be seen that the mating was not done in the same way all the time meaning that the quality of the calibration can differ. Also, if different operators are doing the calibration the quality is likely to differ, for example, the three operators from the CSA were not inserting the connectors in the same way. Another finding from the CSA is that for some calibrations the cable or ECal module needs to be inserted straight and held in the same position for a long time. There is therefore a risk of varying quality in these steps when performed manually. The tests showed that a cobot is suited to maintaining the same position after inserting a connector. This implies that an automated solution can improve the calibration quality for steps that require high repeatability in the insertions and that need the connector to maintain the same position during the calibration.

The quality can also be worse in terms of wear. The test results indicate that a high gripping force is required to be able to perform insertion, which causes the cable to wear out faster than if inserted by an operator. After all the testing, the rubber of the cable in the gripping point was worn out. It was also shown that if smaller misalignments happen there is a risk of more wear. The robot inserts the connector with a higher force than an operator if it misaligns. The robot always inserts the connector with the same force, whereas an operator may feel the misalignment and stop applying force. In Test 2 the connector pin was tiny and it can easily bent if a smaller misalignment occurs. The same follows for the coaxial probe in Test 5 where a smaller misalignment risks damaging the connector, which was something that happened to one of the probes during the testing. It is possible that this type of damage can be mitigated when using reference systems instead of manual programming as the angular error should be smaller when using properly calibrated reference systems. Due to the small size of the connector, it can be hard to discover if the connector is deformed/damaged or not. The quality of the testing or calibration may be affected if a damaged component is used and not replaced. A damaged component also risks damaging the unit under test. But since the connectors closest to the unit under test are the ones which will experience the largest amount of wear, these have to be checked frequently anyway to ensure that the component is not damaged or worn. This can be done by for example performing a daily return-loss measurement and a visual inspection. In Test 4 there was more friction if a smaller misalignment happened and these connectors would wear out faster. If this is done manually, an operator can easily feel the misalignment for this connector type and thereby prevent the wear.

Availability

In terms of change in planned busy time and production time, the test results indicate that connector mating can be performed with enough quality to be done without an operator, given that the calibration procedure is designed to work without SMA connectors. This enables calibration at any time even if there are no operators present, which will result in an increased possibility of using the test-equipment. How much the planned busy time and production time will increase depends on how often calibration is required. In the first case, with shorter calibration intervals, there is a higher risk that calibration will need to be performed when there are no operators present, for example at night or during weekends. In such a case, an automated solution will make the biggest difference in terms of planned busy time and production time. The second case is if it is assumed that calibration needs to be done approximately once a week. The planned busy time from this point of view will not change for an automated calibration solution, as the production can be scheduled so that an operator is working when calibration is needed.

The KPI presented in Section 4.4, is dependent on the planned busy time, which means that if an automated calibration solution allows more planned busy time, the production time will also increase by a similar amount, leaving the KPI essentially unchanged. As the testing of the products is carried out in the same way in both cases, the ratio of production time to planned busy time remains the same for both scenarios.

One of the main ways in which the KPI can be affected is by reducing the calibration time. Calibration can be thought of as a setup time and a reduction in setup time will increase the production time, and consequently increase availability. However, it is important to note that if an automated solution provides the opportunity to increase the planned busy time, for example, through overnight testing, then the number of products tested per week will increase. Increasing the number of tested products is relevant, as the process is considered to be a bottleneck. A major change in the number of products tested per week will only occur if calibration needs to be done frequently, which would hinder full-time production. For example, if it needs to be done twice a day, and with 12-hour intervals, this would lead to one of the calibrations needing to be performed outside standard working times. If the robot can not handle this, it would lead to testing being stopped 12 hours after the first calibration and result in downtime. However, if the robot can handle the calibration, testing and production can continue as normal. Otherwise, with less frequent calibration intervals, the planned busy time and production time will be similar whether an operator or an automated solution is used. The reason for this is that it is possible to schedule manual calibrations during standard working hours for less frequent calibration intervals, for example, if calibration is only required a maximum of once or twice a week.

Another outcome from the tests indicates that the insertion process will be comparable to that performed by an operator. For some connectors, the robot is slower than an operator, while for others, it is faster. Overall the cycle time is similar for the fully manual and the automated process. However, the robot will be able to work directly when an automatic calibration sequence is done. During the CSA there were occurrences when the calibration was paused because the operator left the calibration to perform other tasks, explained in Section 5.2.1. Often the operator would walk away and do something else in between each of these operations, which is productive from a holistic perspective, but not for the calibration operation. The equipment did not notify the operator when the calibration of the current port was finished which resulted in the operator not knowing when to come back to move the device and test the next port. Therefore a lot of unnecessary wait time was introduced. By using a robot in the way that is done for the tests, the robot would start the process of calibrating the next port as soon as the previous one is finished. Also, some of the calibration processes can take a long time and the operator needs to take breaks. The robot will reduce this type of waiting time as it does not need breaks and is present for instantly starting a process step. Shorter calibration times improve the availability of the test-equipment since less time will be spent calibrating the test-equipment and more of the planned busy time will be used for production time, see Equation 4.1.

A robot follows the same calibration steps each time, which means that no steps are skipped. The CSA showed that all the stations had quite repetitive steps and it happened that some steps were missed. This may not affect the quality as the operator will notice this at some point during the verification. However, this may have an impact on the availability since steps may need to be repeated, thereby increasing the calibration time.

An automated solution will be able to do the calibration at any time. A benefit of this is the facilitation of production planning. If an operator performs the calibration, the production needs to be scheduled accordingly because the calibration needs to occur during working hours. Otherwise, it will result in losses in planned busy times if calibration needs to be done during, for example, the night or the weekend.

The availability can also decrease depending on if something goes wrong. The consequences of the robot doing something wrong will probably be worse than an operator doing wrong. The robot may damage components in the test-equipment resulting in longer downtimes of maintenance. Longer downtimes will result in less production time and thereby lower availability of the test-equipment.

Case Example

To give an example of the impact discussed previously, some of the expected impacts will be quantitatively presented for a possible case. This case is based solely on the tasks performed in Station 1, and is subsequently not an estimation of the new calibration procedure but rather an evaluation of the difference between an automated solution and manual calibration in Station 1. During the CSA some approximate cycle times were collected. Together with cycle times collected during the empirical testing, an approximation of how the calibration process could be impacted with an automated solution is presented in Table 6.2. The reason why quality is not included in this case is that it is much harder to quantify and approximate the eventual change.

The Tier-1 calibration is set the same for both cases since it was shown in the CSA that the Tier-1 steps include connecting and disconnecting threaded connectors multiple times, which the cobot could not handle. Therefore it is assumed that the operator still performs the Tier-1 calibration.

The first cycle time that differs is the alignment of tools. For example, when using the lifting table for aligning the ECal module with the 16 ports. The cobot can efficiently perform this type of alignment, as discovered during the tests which reduces the time it takes. The second differing post is the wait time for when the operator was not present to start the next step of the process due to walking away and working on other tasks. This wait will be eliminated when using a cobot as the communication between the robot and the PLC is rapid and the robot can be initiated instantly. The time for fetching tools that were not available when needed also differs. This wasted time is eliminated when using the cobot as the tools will be present at the workstation. Finally, the quality check performed for the finished calibration can possibly be reduced through checking the reference values throughout the robot program automatically, instead of manually verifying them. This number however is a bit more uncertain than the other changes due to not investigating the digital automation during the tests performed. The reason why the reference frame calibration is not included in the column for the cobot is that it is possible to parallelise the task by performing it during the Tier-1 calibration when the operator is not present.

Table 6.2: Case example of calibration performed manually versus with a cobot for Station 1.

Without Cobot	(min)	With cobot	(min)
Tier-1		**Tier-1**	
Calibration by operator	30	Calibration by operator	30
Tier-2		**Tier-2**	
16 port calibration time	140	16 port calibration time	140
16 port alignment of tools	5	16 port alignment of tools	1
3 port calibration time	50	3 port calibration time	50
3 port alignment of tools	7	3 port alignment of tools	3
Wait (operator not present)	16	Wait (operator not present)	0
Fetch forgotten tools	5	Fetch forgotten tools	0
Check calibration quality	15	Check calibration quality	7,5

Summarising the time in the table and rounding up to the nearest minute gives a total time of 269 minutes for the manual operation and 233 minutes for the calibration with a cobot. If the whole calibration is seen as a setup time, this means that the availability of the test-equipment will increase by a factor of approximately *269/233 = 1.1545...*, an increase of 15.5% for this case. It is important to note that cycle times are based on one measurement of Station 1. Factors such as walking away and fetching forgotten tools may differ for every calibration or operator. These times contribute significantly to the difference in availability, as shown.

6.3.2 Process Design

Another way that the test results are influential is for the design of the process and the workstation. These insights can then be used as guidelines for how to shape the process.

Level of Automation and Collaboration

It is now possible to obtain an idea of how the tasks that could be present in the future calibration workstation can be classified in the models presented in [55], see Table B.1. The LoA_c can be expected to move from the current level of 3 to level 4. When a cobot is introduced for the calibration it is expected that the robot can handle most of the tasks, judged by the results of the tests. The role of the operator would be to intervene if the system fails or if any difficult tasks are present. It might even be possible to achieve level 5 if the process and workstation are well-designed and refined. If multiple tasks require an operator it is possible that the LoA_c has to stay at level 3, but no information about such tasks being present in the new factory has been obtained at the time of writing this report. The LoA_p is expected to change from level 2 to 3 due to the change from adjustable tools to specialised grippers in the new factory, comparable to the way it did during testing. The solution is not expected to be able to solve occurring issues autonomously as these are often quite complex and varying, as observed during the CSA, see Section 5.2.1 for an example.

With these results in mind, it is appropriate to decide on what LoC that could be suitable, just like the authors of [55] did when evaluating the tasks of an assembly. Since the project is focused around contacting and has few known varying operations it is considered as one task when making the evaluation. With a LoA_c of 4 and LoA_p of 3 the operation falls within the collaboration zone as presented by [55]. This means that some type of collaboration between the cobot and the human is appropriate.

As the robot is evaluated as capable of performing most of the operations on its own, either coexistence or synchronisation are viable selections of LoC, see Figure 2.1. The LoC is heavily dependent on how the future station will look. If only contacting is present like in the test cases, then coexistence is appropriate as the only time an operator will need to enter the workspace of the robot is if the process fails and has to be corrected by an operator, which is the scenario that is deemed most probable judging from the information obtained during this project. However, if new process steps are implemented that are more complex and have to be done by an operator it is necessary to use synchronisation. The reason why cooperation is excluded as an option is because the current process of calibration has been identified as a linear procedure. The calibration steps are performed in succession and typically the manual work is shorter than the time it takes to calibrate a port. This means that if the process is redesigned to perform several calibrations of ports at once, the manual work can still be performed linearly since the robot will have time for manual work before the last started calibration is finished. The project spent a limited amount of work investigating how calibration steps can be performed simultaneously which means that the current process design sets the LoC. Also, not many of the steps require manipulation of several objects at the same time, and when they do it is deemed more reasonable to solve these steps with smart fixtures instead. This in combination with the linearity of the process makes full collaboration a less viable option. The efficiency in completing these complex steps is also believed not to be improved with a full-on collaborative solution due to the robot obstructing the workspace and abilities of the operator and not being able to work fast enough with an operator that close.

Important to mention is that ideally the calibration procedure should be broken down into tasks and each task evaluated individually as this is the best way to avoid limiting the process to a specific LoC [55]. However, since there is a lack of information regarding how the exact process tasks of the future calibration will look this is not an option. Finally, the LoSr of the operator is expected to be **Intermediate**. The steps performed during calibration are well-documented and relatively straightforward to follow. However, the operator must possess a background understanding of the calibration process and also knowledge about the basics of the cobot to be able to calibrate the TCP or reference frames, for example. Keep in mind that this LoSr does not cover the troubleshooting or error handling of the cobot as this could require skill levels of up to **Expert** to understand what has caused the error and how to fix it.

Operator Safety

As discussed in Section 2.3.6 and by many other authors, safety is an important aspect to consider when implementing both industrial and collaborative robots [19], [83], [84]. As previously discussed a LoC of type coexistence or synchronisation is expected. As presented in Section 6.3.2 the most likely LoC to be appropriate for an automation solution in this case is coexistence. According to research done, it is appropriate to use safety-rated monitored stop, and SSM as well as power and force limiting at this level of collaboration [85]. Furthermore, synchronisation requires no additional safety measures according to the authors. Therefore a transition from coexistence to synchronisation, depending on the requirements of the station, would not be a problem in the future through investing in the safety needed for coexistence. These types of safety mechanisms were discussed in Section 2.3.6. The robot already has power and force limiting built in, but to use SSM or safety-rated monitored stop some additional technology is required such as light curtains, laser scanners or camera systems [86]. As SSM is advocated for it would be advisable to use laser scanners or a camera system as a light curtain is not enough for SSM, but only for safety-rated monitored stop.

6.3.3 Gap Between Tests and Reality

When it comes to the tests they are performed in a controllable environment where only the necessary equipment is within working range. When it comes to the real world, the workstation where the collaboration takes place can be expected to include elements that were not present during testing. Cables could be unpredictable and lead to obstruction of the robot paths or make the process more difficult. Operators could make errors such as bumping into the robot, placing items foreign to the robot within the working space or incorrectly adjusting equipment. Another factor is the choice of materials for the equipment used, impacting behaviour such as friction or flexibility. A further varying factor is the environmental differences such as humidity and temperature. These factors increase the gap between the environment in which the tests were performed and the real production and could have an effect on the differences between the test results and real results, which is a limitation in the results of this work.

6.4 Suggestions for Automation at Saab

For Saab to efficiently be able to make use of the results of this project, it was decided to reformulate the findings into a set of recommendations. This is important as it bridges the gap between the findings and implementation in a real production scenario. Furthermore, the anticipated impacts on the manual problems identified during the CSA are presented in Appendix D.

6.4.1 General Suggestions

While many of the takeaways from the testing are presented in Section 6.3, some were considered especially important. Test 5, see Section 5.4.5, gave some valuable insights about the design of the setup. While the chamfered holes did not perform better than the non-chamfered holes, the holes without chamfer still indicated difficulties in connecting. This is expected to increase even more when the robot works in reference frames rather than online programming. The takeaway of this is the importance of not only trying to have the automated solution as advanced as possible for solving a task but rather redesigning the task to facilitate the automated solution. This is an especially important takeaway when trying to implement automated solutions in a fully manual production environment. Instead of trying to do exactly what the operator has manually been doing with an automated solution, try redesigning the task so that an automated solution can perform it more easily. One example of this is the concept of guides used in Figure C.

Furthermore, Saab should look into the calibration procedure. As mentioned in Section 6.3.2 the procedure is linearly performed. Without the cognitive load on operators, it could be valuable to check if it is possible to perform multiple calibration steps in parallel, potentially saving cycle time.

6.4.2 Grippers

There are multiple aspects to consider for the grippers used. The type of gripper is one important aspect. There are multiple differences between electric and pneumatic grippers, as discussed in Section 2.3.2. It has shown important to regulate the pressure of pneumatic solutions depending on the type of gripper used and what is to be grabbed. But as mentioned in Section 5.5.2, an electric gripper is sufficient for gripping the cables. To uphold the flexibility and not rely on a pneumatic air supply, an electric gripper would therefore be the preferred choice.

A second aspect is the design of the grippers. The grippers in the tests were specifically designed for the cable types. The tests showed the importance of having a specific gripper to be able to solve the insertion tasks. Cables are linear deformable objects and the literature supports that deformable objects generally need specific grippers compared to handling rigid objects [87].

The gripper fingers were designed to grip the connectors close to the end of the cables, where they are often more rigid. Having a gripping point further out in the cable will result in a more complex task for the robot since it is more affected by deformability. The handling of deformable objects by a robot needs to overcome some technical challenges. The challenges of deformable objects include their high number of degrees of freedom, their difficulty in sensing deformation, and their complexity of non-linearity in modelling the deformation [87]. This means that gripping closer to the rigid part of the cable will facilitate the task since it reduces the deformable behaviours and the mentioned challenges are minimised. Another factor for insertion is the risk of damaging components if the connector is pushed in too far, as described in Section 5.4.1. Therefore grippers should be designed to have some give in their final position, for example by including a dampening spring system in the grippers where this problem is present.

Another important aspect of a gripper's fingers is the impact of the wear over time and other factors such as tool changes that affect the TCP position. This must be taken into account, given the high precision required. Operators need to be taught how to re calibrate the TCP for situations when this might be required and grippers must be designed in a way that minimises the wear of the components.

6.4.3 Contact Types

From Test 3, see Section 5.4.3, it was discovered that the SMA-type connection present for the coaxial RF cable posed multiple problems for an automated solution. Therefore it is recommended to avoid steps that require disconnecting and inserting threaded cables during calibration.
Another recommendation is to in the future think more about the choice of connectors that need to be unplugged and inserted frequently. If it is possible to replace the SMA type and meet the requirements, this is preferred from an automation point of view. Connectors that are preferred are for example a slide-on connector, like in Test 4, or a BNC connector.

If the SMA connector can not be substituted or removed through smart process design, and calibration is done when operators are not present, it is worth continuing to design a tool that can solve the task for the UR5e robot. Another recommendation is otherwise to investigate the possibilities with a dual-armed robot since it may eliminate the need for an advanced tool. However, if operators are to be present during calibration then the task of connecting the SMA connectors could be delegated to operators. This would change the LoC to synchronisation and not allow for calibration in the absence of operators which limits flexibility in production planning.

6.4.4 Computer Vision

There are multiple aspects to take into consideration when determining whether or not to use a vision system. Furthermore, should the decision be made to implement a vision system, a wide variety of options are available.

As discussed in Section 2.3.3 and Section 4.2.2 there are many benefits and functionalities of using vision systems. One argument for vision is that the robot will move around to perform tasks at different workstations and the vision system could help with localisation of the robot and identification of the surroundings. Another benefit of including vision is the bar code reading or object identification which could help identify which fixture is placed in the test-equipment, and then execute specific programs based on that information. Some of the identified drawbacks of a vision system are cost and complexity. The application of vision extends beyond the calibration process, which is a factor that can not be forgotten when determining if a vision system is worth it. Other tasks where it could prove useful can be for component picking in racks or for quality inspection.

When considering the implementation of a vision system there are many variants to choose from. Two common alternatives that have been identified in other research applications were compared in Section 4.2.2; Intel Realsense 435 and the Robotiq wrist camera. It is here important to remember that these two cameras have been identified as two alternatives within two common categories of camera types and that there is a myriad of products which fulfil similar criteria and functionalities.

The steps that are to be automated at Saab are of a characteristic that puts high demands on precision, quality and flexibility which makes the Intel Realsense d435 appealing. For applications similar to what was done in the article by Sun [34], stereo vision with depth perception gives another useful dimension of information. For example, the case was presented in Section 4.2.6 where [71] used the depth camera for detecting sockets. The Robotiq wrist camera comes at a steeper price than the Intel Realsense 435, probably due to all of the extra functions that it includes and the increased compatibility. There are reasons to believe that it is not sufficient for the complex task at hand. To give a case in point the project by [88] deemed the camera unfit to detect small components in a relatively simple environment, with a high contrast and level background. This suggests that the Robotiq wrist camera, utilising its built-in features, is probably not suitable for more complicated environments like the one here at Saab. Therefore, a camera like the Intel Realsense 435 would be a better fit for the task.

There is potential in using vision for similar tasks as in this project but there exists numerous aspects which advocate against using it. First and foremost is the infrequency of the calibration procedures at Saab. The positives of a vision solution are overshadowed by the implementation cost and time along with the complexity it brings to the system, as it has been concluded that a basic camera system is not enough to handle the tasks at hand. If the calibration would have needed vision for some tasks there would still be an argument for implementing it anyway. There is a possibility to perform tasks like calibration of reference frames and positioning of the robot with other technologies, such as laser distance sensors. The tests also show that it is possible to have fixed positions for equipment. These were the two main use cases for vision that were identified, and they can be solved through other means, which indicates that vision is not necessary for an automated calibration process.

6.4.5 Sensors

The sensors studied in this project were primarily laser distance sensors, as they are relatively inexpensive but provide some flexibility, good repeatability and low interference with RF equipment. As discussed in Section 2.3.1 & Section 4.2.1 there are several methods to perform calibration of the cobot, to ensure that it will accurately locate the objects in its workspace. This is one key area in which laser sensors have been identified as a useful technology. These sensors are suitable for calibrating the robot's position and reference frames, as they can achieve high repeatability in their measurements. It is also possible to control the elevation of the component being calibrated to ensure that a contact is inserted with the correct distance, which is important according to findings from the tests, as presented in Section 5.4.1.

Another potential application is the implementation of safety checks, such as controlling the height of the circuit board when it is placed in the fixture to see that it is properly seated. While this is not required for the calibration process, it does offer added value. For these reasons, it would be advisable to consider including a diffuse reflective laser distance sensor in the automated solution. Important when using these is to check data sheets for sensing performance on different materials and ranges, as the linearity of sensors could differ when it comes to larger measuring distances or certain materials, which has to be accounted for to receive the best possible measurement.

6.5 Societal and Environmental Implications

From the results of the tests, Section 6.3 and also the analysis of LoC and LoA, Section 6.3.2 it is determined that a robot should be able to handle most of the tasks and also that the solution will reach a higher level of LoA_c (cognitive LoA). This means that the operator will be offloaded both physically and cognitively. One example of this is cases like the one observed in the CSA at Station 1 where the operator had to swap between tasks due to long calibration times. Through using the robot for repetitive tasks, the operator will be offloaded from the repetitive strain which can be demanding both physically and mentally [89]. This will allow for the operator to not jump between tasks, which is another cognitive demand according to the authors as human capabilities decrease when our attention is divided. Divided attention could lead to an increased risk of injury or decreased quality which is one of the reasons why the automation solution is beneficial. However, it is unrealistic to anticipate a completely frictionless transition to automation. Numerous factors discussed by [90] regarding the implementation of Industry 4.0, such as feelings of inadequacy, concern about the loss of jobs or feelings of over-supervision, also carry a risk of appearing to varying extents. The authors present multiple ways of dealing with these problems including proper communication of why technology is adopted and training/upskilling. Furthermore, they mention the importance of participation, which aims to include the operators in development to facilitate understanding and also make sure to include the opinions of operators in the new solutions.

As for the environmental impact, there are multiple aspects to consider. This project is mainly focused on the availability and quality aspects of the production and how the solution will affect these parameters, see Section 6.3.

Starting with quality there are multiple factors presented pointing towards an increased quality of the calibration, such as the consistent nature of the robot. Through improving the quality of the calibration it is possible that it has to be done with less frequent intervals, this would then mean that more time will be spent on actual value-adding activities (production) and less time for calibration, assuming similar or shorter calibration duration. This is beneficial from a resource efficiency perspective. Furthermore, equipment which is better calibrated will mean that the testing of the products will more accurately differentiate worse products from good products. This leads to a reduction in false negatives and false positives in testing. Products that are of an acceptable quality will not be retested unnecessarily, while products that are closer to being nonconforming will not be accepted and will not lead to further waste of resources due to quality issues.

Considering availability, the outcome is less certain. As described in Section 6.3, many factors influence how availability is affected. An increase in availability signifies that a greater proportion of the planned busy time is used for actual production, as explained in Section 4.4. Therefore the resource efficiency will increase as less time is spent on non-value-adding activities.

Safety

The results from this study present multiple functions to enhance the safety of operators which is a part of social sustainability, see Section 6.3.2. Safety for operators can be connected to both Industry 4.0 and Industry 5.0 as discussed in Section 2.2.2 and Section 2.3.6, adding to its significance in the implementation of automation. Safety is of particular importance when considering the concept of human centricity and bringing humans back into the loop, which Industry 5.0 aims to do. Research states that safety is one of the main operator-related challenges in collaborative workspaces [91].

6.6 Research Questions

In this section, the proposed research questions will be addressed.

How can automation technologies be implemented to improve the availability of the test-equipment and calibration quality?

Automation technologies, if adapted correctly, have the capabilities of both improving quality as discussed by [7], and availability as shown in [77]. Other researchers have explored the concept of automating high mix low volume production with success regarding quality. Further described in Section 6.3 are multiple aspects of how availability and quality can be expected to change with the implementation of automation.

In terms of quality, it was shown that automation can improve the quality of the calibration because the robot is better at some tasks than a human. A cobot will do the calibration in the same way every time, compared to what was discovered in the CSA, presented in Section 5.2.4, where working procedures can differ. The test results also showed that the robot was good at inserting connectors straight and maintaining the same position if needed. The tests showed that the connectors will wear out faster for an automated solution. Further, it was presented in Section 6.3 that the robot will insert misalignments with a greater force meaning that there is a higher risk of damaging components compared to an operator. This can affect the quality of the calibration negatively if the components are not replaced directly.

The implementation of an automated solution is unlikely to significantly impact the KPI availability. One of the ways to improve the availability is to reduce the calibration time and from the CSA it was shown that the calibration sequences in the software make up most of the calibration time which can not be affected by a robot, as discussed in Section 6.3. In the tests, the robot exhibited comparable insertion times to those of an operator performing a similar task. However, the calibration process frequently encountered obstructions when the operator was performing the calibration, which was presented in Section 5.2.4. The calibration process could be paused due to the operators leaving the calibration for either other work or to take a break. A robot can work continuously, eliminating these times that pause the calibration, thereby reducing the calibration time and improving the availability.

If calibration needs to be done frequently (multiple times per week) an automated solution will increase the total available production time but the KPI will not be affected since it also increases the planned busy time, see Section 4.4 & Section 6.3.1. However, an automated process with frequent calibrations will still increase the number of products that can be tested in a week even though the KPI availability does not change.

What automation technologies are most suitable for calibration of the test systems?

There are multiple research projects independently utilising technologies that were covered in this project, and also combinations of them, see Section 4.2 and Section 4.2.6. The testing done in this project suggests that the UR3 robot is sufficient for performing tasks similar to both the ones present in the calibration procedure existing today and in the near future. Therefore the reasoning in Section 5.5.1 suggests that the UR5e also perform well enough for the task at hand.

There exists research articles highlighting the powerful areas of application using vision with machine learning in unison with collaborative robots [34], [66], [71]. However due to the nature of the calibration procedure vision has been found to not be necessary for performing the calibration tasks automatically, elaborated in Section 6.4.4. One reason for this is the possibility of using other supporting technologies which are less expensive and less complex, such as laser distance sensors for tasks where vision would have been an option. Consequently, there is no need for machine learning algorithms as the main purpose of machine learning covered in this project was for vision applications.

Furthermore, suggestions concerning hardware such as grippers, fixturing, connector types and operational demands are presented in Section 6.4.1. These types of demands have proven especially important due to high requirements for precision and quality.

Finally, it is necessary to include technology that keeps operators safe and reduces the risk of accidents, which is of utmost importance when implementing automation [86]. Technologies for SSM and safety-rated monitored stop should be in place, as elaborated in Section 6.3.2.

What are the obstacles for implementing automation solutions in a production environment with intricate processes?

In a low volume high variety production environment which is present at Saab, there are often complicated processes that are predominantly designed around manual operation. This manual-centric approach significantly complicates efforts towards automation.

As presented in Section 5.3.1 there are multiple identified challenges with implementing automation in this type of complex environment. Many of the general problems could be connected to a couple of common factors. Primarily high precision is required for many of the operations, meaning that high demands would be set on any implemented automation solution from a tolerance and performance perspective. Secondly, when multiple parts are handled at once such as connecting two cables through an adaptor there is often a reliance on human dexterity, which is complex to replicate in a gripper [27].

Third is the complexity of components used for the calibration task which requires an active decision on either investing in advanced automation solutions or swapping to other components which could be both costly and also not always yield sufficient quality. The testing done in this project serves as an insight into these kinds of components and also shows the difficulties of transitioning from a manually performed task to an automated version. Additionally, regulatory compliance becomes a crucial aspect, particularly when the process requires capabilities beyond those provided by standard manufacturer specifications. This regulatory aspect, briefly addressed in Section 4.3, further adds to the complexity of implementation.

6.7 Recommendations for Further Research

Following the completion of this project there are still some remaining unanswered questions that have surfaced.

It was quite clear that the information about application of automation in low-volume high-variety production environments is quite scarce. It appears that there are some knowledge gaps in research regarding the implementation, where the focus is on flexibility rather than cycle time. Further information about this area could exist within companies that work with the said area but has yet to be researched in greater depth.

One of the knowledge gaps for specific tasks of a cobot that were found, is the manipulation and connection of threaded cables, see Section 5.4.3. Information about how to connect nuts to bolts with torque drivers and how to connect other types of cables (BNC for example) exist. There were no findings about specific procedures, grippers or strategies to do this with an SMA-type coaxial cable like the one in Figure 5.2. Since this type of connector is frequently used for calibration and RF equipment it would be interesting to find a solution to support automation of this task. One suggestion is to test a dual-armed cobot for the insertion of SMA connectors, for example, ABB's YuMi. A dual-armed cobot solves the problem of holding the cable in place and at the same time entering the nut. Another suggestion is to further try to develop the concept presented in Section 5.4.3, and try to introduce solutions for mitigating the described issues.

During the testing done in the project the robot used was limited to not using coordinate systems, see Section 5.4.6 and 6.2. Further research on the ability to create accurate reference frames for detailed and small applications would be interesting to allow for more flexible automated solutions within this type of automation.

7

Conclusion

The thesis aims to analyse how the implementation of automation technologies impacts the availability of the test systems and the quality of the test system calibration at Saab. The potential of improving these parameters, and in turn impacting the production positively, was a driving factor for carrying through with the project. The work is centred around, but not limited to, collaborative robots and their associated technologies. The objective and desired outcome is to use the information gained from the answered research questions as leverage in Saab's journey towards smart manufacturing.

Multiple tests were conducted to automate common calibration process steps. The production environments in which these are performed often involve processes designed for manual work, featuring steps that are inherently difficult to automate due to intricate hardware, confined workspace, complex tools, and reliance on human dexterity. The results indicate that a collaborative robot is sufficient for performing a majority of the tasks, although certain components may require substitution or operator intervention to enable efficient automation. In combination with the knowledge gained from the literature study, the results reveal that it is possible to use vision for some of the tasks. However, it is concluded that simpler technology alternatives which are less complex to implement and maintain, still can perform the necessary functions for successful task automation. Therefore, vision is not considered the optimal solution.

The tests showcase the robot's capability in handling various types of contacts, leveraging its precision which proves highly advantageous for contacting tasks. The project includes design aspects of the collaborative workstation, ensuring the implementation of appropriate safety measures. Several beneficial parameters concerning quality have been identified, with the repeatability and precision of the robot being crucial factors. Although there is a clear need for measures to address equipment wear. Under the right conditions, particularly reliant on calibration intervals, the implementation of automated solutions can yield numerous positive effects on test system availability.

The pursuit of automation within Saab's complex production environment shows the organisation's commitment to smarter manufacturing. Despite the potential challenges of complex automation, the benefits of successful implementation should not be underestimated. This project demonstrates the promising potential of strategic automation initiatives.

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A

Interview Questions and Observations

The following appendix present what was observed during the calibration process and what was asked in the semi-structured interviews.

List of observations made:

- What type of connectors are used?
- What information does the operator use for decision-making (visual feedback-/error codes etc)?
- What tools are used for the job?
- Precision / heavy steps /reach
- Did something unexpected happen, how did the operator handle this?

List of interview questions:

- When do you need to plug in or plug out the cables?
- How often is the calibration needed in different levels?
- What are the most common quality problems during the process? Something that makes the process time-consuming?
- How often do errors occur and what are their characteristics?
- How much of the work is to follow instructions vs own initiative?

B

Level of Automation

A taxonomy of Level of Automation developed by [55] is presented in this appendix. The LoA is specifically developed for cobot applications and it contains a cognitive aspect and a physical aspect of automation.

Table B.1: Levels of Automation (LoA) for Collaborative Robot Applications as presented by [55].

Level of Cognitive Automation ($\mathbf{LoA}_c$)	**Level of Physical Automation ($\mathbf{LoA}_p$)**
Totally manual (1) – The human creates his/her own understanding of the situation and task at hand and develops his/her course of action based on his/ her previous experience and knowledge. No automation is not involved in decision-making. For example, operators use previous knowledge and experience	**Totally manual (1)** – No use of a robot or any mechanical tool by humans to complete the physical task. For example, no used tool.
Basic task (2) – The human gets overall information on what to do or a proposal on how the task can be completed. For example, checklists and manuals.	**Basic task (2)** – The human or robot uses a flexible tool to complete a task. For example, the use of a multiple-purpose tool like an adjustable spanner or a gripper capable of picking- &-placing different sizes and shapes.
Instructions (3) – The human gets detailed instructions on how the task should be done. For example, assembly instructions.	**Instructions (3)** – The human or the robot uses a fixed tool to complete a task. For example, the use of a specialised gripper.
Supervision (4) – The human observes the automation performing the task and decides on intervention. For example, an Andon alert is triggered calling for human repair/fix intervention.	**Supervision (4)** – A robot self-selects the best possible solution for a given task and guides the operator in solving any issue if this occurs. For example, the use of an adjusting tool.
Totally Automatic (5) – All information and control are handled by automation. The operator is not involved. For example, autonomous manufacturing cells and smart workstations.	**Totally Automatic (5)** – The system handles all information and control by itself. For example, autonomous manufacturing cells and smart workstations.

C

Illustrations of Test 5

The appendix illustrates how the fixture in Test 5 was designed to hold the connectors. It also illustrates a problem that was discovered during the testing with one of the designs. An ideal design from an automation point of view is presented to handle this problem.

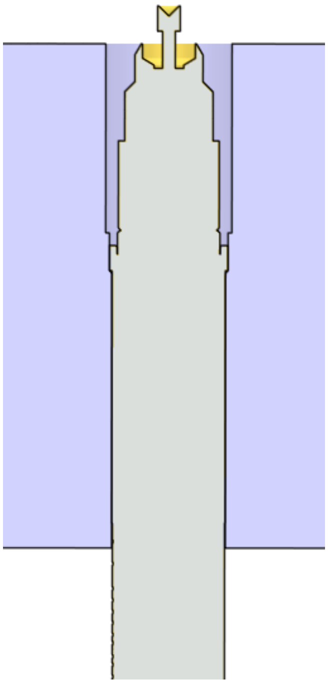

Figure C.1. Illustration of how the connector is seated in two holes of the fixture for Test 5.

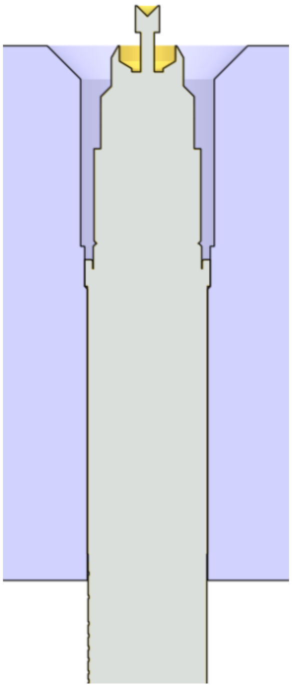

Figure C.2. Illustration of how the connector is seated in two chamfered holes of the fixture for Test 5.

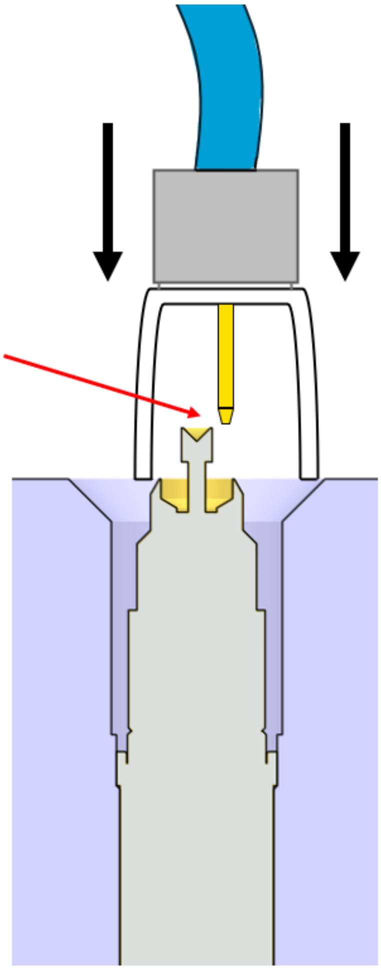

Figure C.3. Illustration of the problem with having a countersunk type chamfer for Test 5.

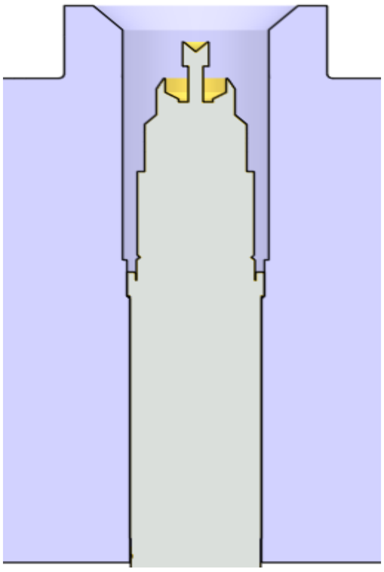

Figure C.4. Illustration of how an improved guide would look for the type of connector used in Test 5.

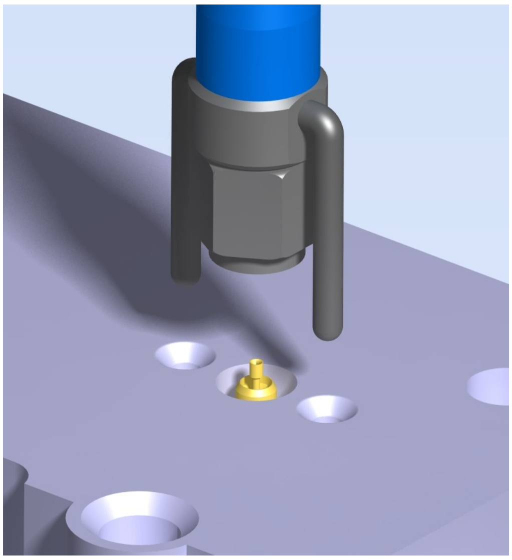

Figure C.5. Illustration of how a potential alternative guide could look for Test 5 (above insertion).

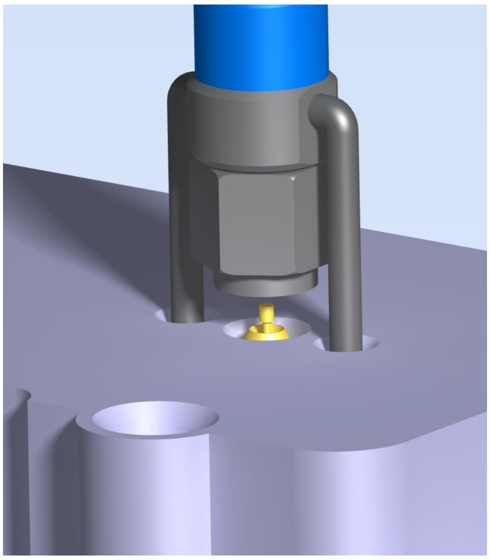

Figure C.6. Illustration of how a potential alternative guide could look for Test 5 (during insertion). Notice that the connector has been guided correctly before contact with the golden probe.

D

Answers of problems for manual steps

This appendix was made to answer the problems for the manual steps identified during the CSA, see Section 5.3.1.

Precision and accuracy are important for calibration contact points and the angular, horizontal and vertical deviations need to be kept low.

As discussed in Section 6.3.1, these two performance parameters are only expected to increase for an automated solution.

Repetitive and time-consuming for the worker to test all the ports as there is a time delay between each test.

The most likely solution for the collaborative application is coexistence or synchronisation, see Section 6.3.2. Furthermore the tests highlight the capabilities of the robot to perform the monotonous tasks identified, thus meaning that the operator will be offloaded and not have to spend time or perform the repetitive work.

Complicated threaded connections of the cables that need to be disconnected and reconnected in some of the calibration steps, see Figure 5.2.

No solution was found for automating this type of process, see Section 5.4.3 and Section 6.2.3. First and foremost it is recommended to investigate where it is possible to swap the SMA connectors for other types in future products, if the transmission properties of SMA connectors are not required. If the swap is not possible, the recommendation is to either further develop the concept presented or try other automation solutions, such as ABB's YuMi mentioned in Section 6.7.

Problems with the snap-on connections as they sometimes get displaced during calibration and have to be re-attached using a special tool.

These types of connectors were not investigated during testing as they were not identified to be present where the automation solution is to be implemented.

Cables should not be bent to avoid affecting the RF signals.

During the testing major bending of the cable was done to test extreme cases for grasping. But when it comes to the operation of picking and connecting cables there is no need for the robot to bend the cable more than a human would have.

The ECal modules were not fixed in any way, which could cause them to tip over or have uncertain positions that in theory can affect the calibration quality.

This could be solved with simple fixtures to place the ECal modules in. This design would of course depend on how these are used in the new factory, but for a step similar to the one in [Station 1], simple fixtures would be sufficient.

When connecting cables without ECal module, they were not fixed in place, causing difficulties for the operator and also uncertain cable positions.

This was when two cables were connected using an adaptor. This type of step should be avoided at all costs. Handling multiple deformable objects at once is very problematic for a robot, especially if threading is needed. Test 3 shows that even if the object that is to be connected with threads is stationary, the task is complicated.

There were several confirmation checks by the operator for the ID numbers of the kits used to make sure they correlated to the ones in the software, this was time consuming and could cause confusion.

Through robotic programming there is no need to check the serial numbers as either the calibration kits will be stationary, or they will be picked and placed in the same sequence over and over again. This means that the position of the kits would not change through random placement of an operator or human error.

For some steps in the calibration instruction it was advised to clean the stations through vacuuming and cleaning the contacts. This requires fine motor skills and also identifying dust or grime visually which is not a simple task for a robot.

If included, this would have to be done by an operator. Identification of grime and also cleaning it would be very difficult for a robot in this type of production environment. It would be beneficial to design the process in a way which minimises wear and contamination, to allow for less frequent cleaning intervals. This is to allow for calibration even if operators are not present.

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